



## **SUPPRESSION OF PILOT-INDUCED OSCILLATION (PIO)**

**THESIS**

Donald A. Johnson  
Captain, USAF

AFIT/GAE/ENY/02-1

*DEPARTMENT OF THE AIR FORCE*  
**AIR UNIVERSITY**  
**AIR FORCE INSTITUTE OF TECHNOLOGY**

Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

**SUPPRESSION OF PILOT-INDUCED OSCILLATION (PIO)**

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

Donald A. Johnson, B.S.  
Captain, USAF

March 2002

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

**SUPPRESSION OF PILOT-INDUCED OSCILLATION (PIO)**

Donald A. Johnson, B.S.  
Captain, USAF

Approved:

Date

///SIGNED///

31 JAN 02

Bradley S. Liebst, Ph.D. (Chairman)

///SIGNED///

31 JAN 02

Lt Col David R. Jacques, Ph.D.

///SIGNED///

31 JAN 02

Lt Col J. Michael Phillips, Ph.D.

## Preface

The purpose of this thesis was to develop an algorithm to prevent oscillatory departures and/or longitudinal pilot-induced oscillations (PIOs). Computer simulation and flight test data were used to validate this research project.

The study was conducted under the joint Air Force Institute of Technology (AFIT)/USAF Test Pilot School (TPS) program. I would like to thank my primary advisor, Dr. Brad Liebst (AFIT), who proposed the PIO topic and offered valuable suggestions and insights. Additionally, Mr. Dave Leggett (Air Force Research Laboratory Air Vehicles Division) provided assistance and suggestions throughout the project. Mr. Dave Mitchell (Hoh Aeronautics, Inc.) developed the Real-time Oscillation VERifier (ROVER) switching logic and Matlab code. Mr. Andy Markofski (Veridian Engineering, Flight Research Group, Buffalo, NY) provided guidance concerning the nature of the variable stability system (VSS) and the USAF Variable-Stability In-Flight Simulator Test Aircraft (VISTA), while Mr. Jeff Peer (Veridian) performed safety pilot duties on all VISTA test sorties.

I would especially like to thank the entire HAVE ROVER flight test team for making this flight test project a reality: Flt Lt David J. Ballance, Royal AF, Capt Matteo Maurizio, Italian AF, Capt Vitaly Shaferman, Israeli AF, and Captains Philip M. Cali and Richard F. Bailey Jr., USAF. Super job guys – I was proud to be a member of “Those Meddling Kids”, TPS 01A

Don Johnson

## Table of Contents

	<u>Page</u>
<b>Preface</b>	iii
<b>List of Figures</b>	viii
<b>List of Tables</b>	xiii
<b>List of Symbols</b>	xv
<b>List of Abbreviations and Acronyms</b>	xvii
<b>Abstract</b>	xviii
<b>I. Introduction</b>	1-1
General	1-1
Background	1-2
Objectives	1-7
Approach	1-8
Scope	1-9
<b>II. Theory</b>	2-1
PIO Detection and Suppression	2-1
Real-time Oscillation VERifier (ROVER) Development	2-3
Notch Filter Development	2-5
Aircraft Development	2-7
Pilot Model Development	2-10
Stick and Feedback Noise	2-10
VISTA Aircraft Model	2-12

## Table of Contents (cont.)

	<u>Page</u>
<b>III. ROVER and Notch Filter Simulation Results . . . . .</b>	<b>3-1</b>
Continuous Simulation . . . . .	3-1
Bare Airframe Configurations . . . . .	3-3
ROVER Implementation . . . . .	3-5
<u>PIO Severity Logic</u> . . . . .	3-6
<u>ROVER Conditions Subsystem</u> . . . . .	3-7
<u>Min_Max Logic Subsystem</u> . . . . .	3-11
Additional Simulation Configurations . . . . .	3-17
<b>IV. Flight Test Preparation . . . . .</b>	<b>4-1</b>
Pre-Flight Organization . . . . .	4-1
Flight Test Overview . . . . .	4-2
Test Article Description . . . . .	4-4
Flight Test Aircraft Description . . . . .	4-6
Rating Scales . . . . .	4-7
Flight Test Objective . . . . .	4-7
<u>Configuration Validation</u> . . . . .	4-8
<u>PIO Detection</u> . . . . .	4-9
<u>PIO Suppression</u> . . . . .	4-10
<u>Pilot Performance with ROVER</u> . . . . .	4-10

## Table of Contents (cont.)

	<u>Page</u>
VISTA Ground Simulation and Target Aircraft. . . . .	4-11
Tracking Tasks . . . . .	4-12
Telemetry and Data Collection . . . . .	4-17
<b>V. Flight Test . . . . .</b>	<b>5-1</b>
Limitations . . . . .	5-1
Configuration Validation . . . . .	5-2
PIO Detection . . . . .	5-4
PIO Suppression . . . . .	5-13
Pilot Performance with ROVER. . . . .	5-19
Arriving at a RIV of Four. . . . .	5-30
Handling Qualities with ROVER. . . . .	5-33
<b>VI. Conclusions and Recommendations . . . . .</b>	<b>6-1</b>
ROVER PIO Detection . . . . .	6-1
ROVER PIO Suppression . . . . .	6-2
Pilot Performance with ROVER. . . . .	6-3
Additional Observations . . . . .	6-4
<b>Appendix A. MATLAB® m.files . . . . .</b>	<b>A-1</b>
<b>Appendix B. HAVE ROVER Flight Test Results. . . . .</b>	<b>B-1</b>
Validation Data . . . . .	B-1
Evaluation Data. . . . .	B-23

## Table of Contents (cont.)

	<u>Page</u>
<b>Appendix C. Flight Test Log, Rating Scales, Pilot Comments, and Parameter List</b>	<b>C-1</b>
Flight Test Log	C-1
Cooper-Harper Rating Scale	C-2
Pilot-Induced Oscillation Rating (PIOR) Scale	C-3
Nuisance Rating (NR) Scale	C-4
Pilot Comments and Ratings	C-5
Instrumentation Parameters	C-21
<b>Bibliography</b>	<b>BIB-1</b>
<b>VITA</b>	<b>VITA-1</b>

## List of Figures

	<u>Page</u>
Figure 1-1. Aircraft System with a SAS. . . . .	1-3
Figure 2-1. Notch Filter Bode Diagrams . . . . .	2-6
Figure 2-2. Short Period Handling Qualities . . . . .	2-8
Figure 2-3. Actuator Dynamics with Saturation . . . . .	2-9
Figure 2-4. VISTA Sample Data and Associated Noise Levels . . . . .	2-11
Figure 2-5. Variable Stability System (VSS) Architecture . . . . .	2-12
Figure 2-6. VISTA Model Following Architecture. . . . .	2-13
Figure 3-1. Aircraft System Driven by Theta Track Error . . . . .	3-2
Figure 3-2. Step Input with 35 deg Amplitude and 0.5 sec Duration . . . . .	3-3
Figure 3-3. Aircraft Response to a 35 deg Step Input . . . . .	3-4
Figure 3-4. PIO Severity Logic . . . . .	3-6
Figure 3-5. ROVER Conditions Subsystem . . . . .	3-8
Figure 3-6. Pitch Rate Min_Max Subsystem. . . . .	3-14
Figure 3-7. Elevator Deflection Min_Max Subsystem . . . . .	3-15
Figure 3-8. White Noise Injection into System Model . . . . .	3-16
Figure 3-9. Increased Equivalent System Delay . . . . .	3-17
Figure 3-10. Case A Response with Excess Time Delay without ROVER . . . . .	3-18
Figure 3-11. Case A Response with 200 msec Delay with and without ROVER . . . . .	3-18
Figure 3-12. Case A Response with 500 msec Delay with and without ROVER . . . . .	3-20
Figure 3-13. Case B Response with 40 deg/sec Rate Limiting . . . . .	3-21
Figure 3-14. Case C Response to 35 deg Step and 60 deg/sec Rate Limiting . . . . .	3-22

## List of Figures (cont.)

	<u>Page</u>
Figure 3-15. Case D Response to 25 deg Step Input . . . . .	3-23
Figure 3-16. Aircraft Response to Ramp Input . . . . .	3-24
Figure 4-1. HUD Tracking Task Symbology . . . . .	4-13
Figure 4-2. HUD Tracking Task . . . . .	4-14
Figure 5-1. Pilot 1 - Non-aggressive Phase 2 HUD Tracking Task . . . . .	5-9
Figure 5-2. Pilot 3 - Aggressive Phase 2 HUD Tracking Task . . . . .	5-9
Figure 5-3. Pilot 2 – Non-aggressive Phase 3 HUD Tracking Task . . . . .	5-11
Figure 5-4. Pilot 1 - Phase 3 HUD Tracking Task with and without ROVER	5-23
Figure 5-5. Pilot 3 - Phase 3 HUD Tracking Task with ROVER on. . . . .	5-27
Figure 5-6. Simulink® Simulation of PA Buildup . . . . .	5-31
Figure 5-7. Flight Test Data of PA Buildup . . . . .	5-32
Figure B-1. Closed Loop Time Response for Configuration C (Flt 713 – 43)	B-1
Figure B-2. Closed Loop Time Response for Configuration C (Flt 713 – 46)	B-1
Figure B-3. Closed Loop Time Response for Configuration C (Flt 713 – 47)	B-2
Figure B-4. Closed Loop Time Response for Configuration C (Flt 713 – 48)	B-2
Figure B-5. Closed Loop Time Response for Configuration C (Flt 713 – 49)	B-3
Figure B-6. Closed Loop Time Response for Configuration C (Flt 713 – 52)	B-3
Figure B-7. Time Response for Configuration A (Flt 713 – 2, Open Loop) .	B-4
Figure B-8. Time Response for Configuration B (Flt 713 – 5, Open Loop) .	B-4
Figure B-9. Time Response for Configuration C (Flt 713 – 11, Open Loop)	B-5

## List of Figures (cont.)

	<u>Page</u>
Figure B-10. Time Response for Configuration D (Flt 713 – 13, Open Loop)	B-5
Figure B-11. Time Response for Configuration A (Flt 713 – 16, Closed Loop)	B-6
Figure B-12. Time Response for Configuration B (Flt 713 – 19, Closed Loop)	B-6
Figure B-13. Time Response for Configuration C (Flt 713 – 22, Closed Loop)	B-7
Figure B-14. Time Response for Configuration D (Flt 713 – 25, Closed Loop)	B-7
Figure B-15. Frequency Sweep for Configuration A (Open Loop) . . . . .	B-8
Figure B-16. Bode Plot for Configuration A (Open Loop) . . . . .	B-9
Figure B-17. Bode Plot for Simulink® Configuration A (Open & Closed Loop)	B-10
Figure B-18. Bode Plot for Configuration B (Open Loop) . . . . .	B-11
Figure B-19. Bode Plot for Simulink® Configuration B (Open & Closed Loop)	B-12
Figure B-20. Bode Plot for Configuration C (Open Loop) . . . . .	B-13
Figure B-21. Bode Plot for Simulink® Configuration C (Open & Closed Loop)	B-14
Figure B-22. Hands-off Response for Configuration D (Open Loop) . . . . .	B-15
Figure B-23. Bode Plot for Configuration D (Open Loop) . . . . .	B-16
Figure B-24. Bode Plot for Simulink® Configuration D (Open & Closed Loop)	B-17
Figure B-25. Bode Plot for Configuration A (Closed Loop) . . . . .	B-18
Figure B-26. Bode Plot for Simulink® Configurations A-D (Closed Loop) .	B-19
Figure B-27. Bode Plot for Configuration B (Closed Loop) . . . . .	B-20
Figure B-28. Bode Plot for Configuration C (Closed Loop) . . . . .	B-21
Figure B-29. Bode Plot for Configuration D (Closed Loop) . . . . .	B-22

## List of Figures (cont.)

	<u>Page</u>
Figure B-30. Input power spectral density in Phase 2 for pilots 1 and 2 . . . . .	B-23
Figure B-31. Input power spectral density in Phase 2 for pilots 2 and 3 . . . . .	B-23
Figure B-32. Threshold Parameter Study – ROVER Total Hits . . . . .	B-24
Figure B-33. Threshold Parameter Study – ROVER PIO Hits . . . . .	B-25
Figure B-34. Threshold Parameter Study – ROVER No PIO Hits . . . . .	B-26
Figure B-35. PIOR Comparison – Pilot, HQ 2 . . . . .	B-27
Figure B-36. PIOR Comparison – Pilot, HQ 3 . . . . .	B-27
Figure B-37. PIOR Comparison – Configuration, HQ 2 . . . . .	B-28
Figure B-38. PIOR Comparison – Configuration, HQ 3 . . . . .	B-28
Figure B-39. PIOR Comparison – Rate Limit, HQ 2 . . . . .	B-29
Figure B-40. PIOR Comparison – Rate Limit, HQ 3 . . . . .	B-29
Figure B-41. PIOR Comparison – Time Delay, HQ 2 . . . . .	B-30
Figure B-42. PIOR Comparison – Time Delay, HQ 3 . . . . .	B-30
Figure B-43. Elevator Command and RIV (PIOR Improved, HQ 2) . . . . .	B-31
Figure B-44. Elevator Command and RIV (PIOR Same, HQ 2) . . . . .	B-31
Figure B-45. Elevator Command and RIV (PIOR Improved, HQ 3) . . . . .	B-32
Figure B-46. Elevator Command and RIV (PIOR Same, HQ 3) . . . . .	B-32
Figure B-47. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 4) . . . . .	B-33
Figure B-48. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 1) . . . . .	B-33
Figure B-49. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 3) . . . . .	B-34
Figure B-50. Elevator Command and RIV (PIOR Worse, HQ 3) . . . . .	B-34

## **List of Figures (cont.)**

	<u>Page</u>
Figure C-1. Cooper-Harper Rating Scale . . . . .	C-2
Figure C-2. Pilot-Induced Oscillation Rating (PIOR) Scale . . . . .	C-3
Figure C-3. Nuisance Rating (NR) Scale . . . . .	C-4

## List of Tables

	<u>Page</u>
Table 2-1. Aircraft Configurations and Feedback Gains . . . . .	2-9
Table 4-1. HAVE ROVER Team Test Pilots . . . . .	4-1
Table 4-2. HAVE ROVER Configuration Decoder Table . . . . .	4-4
Table 4-3. Test Matrix for Validation (MOP 1) . . . . .	4-8
Table 4-4. Evaluation Criteria for Configuration Verification . . . . .	4-8
Table 4-5. ROVER Detection Evaluation Criteria . . . . .	4-10
Table 5-1. Flight Test versus Simulation Parameters – Configuration . . . . .	5-3
Table 5-2. Flight Test versus Simulation Parameters – Rate Limits . . . . .	5-3
Table 5-3. Flight Test versus Simulation Parameters – Time Delays . . . . .	5-3
Table 5-4. Evaluation Criteria for Configuration Verification . . . . .	5-4
Table 5-5. Overall ROVER Detection Results . . . . .	5-5
Table 5-6. ROVER Threshold Values . . . . .	5-6
Table 5-7. ROVER Detection Results - Breakout by Pilot . . . . .	5-6
Table 5-8. ROVER Detection Results – Breakout by Configuration . . . . .	5-6
Table 5-9. ROVER Detection Results - Breakout by Rate Limit . . . . .	5-7
Table 5-10. ROVER Detection Results - Breakout by Time Delay . . . . .	5-7
Table 5-11. ROVER Detection Results - Breakout by Tracking Task . . . . .	5-7
Table 5-12. ROVER Detection Results - Breakout by Maneuver Aggressiveness . . . . .	5-7
Table 5-13. Phase 3 ROVER Detection Results with Modified Thresholds . . . . .	5-12
Table 5-14. Optimized ROVER Threshold Values . . . . .	5-12
Table 5-15. ROVER PIOR Separated by Pilot . . . . .	5-14

## List of Tables (cont.)

	<u>Page</u>
Table 5-16. ROVER PIOR Separated by Configuration . . . . .	5-15
Table 5-17. ROVER PIOR Separated by Rate Limit . . . . .	5-16
Table 5-18. ROVER PIOR Separated by Time Delay . . . . .	5-17
Table 5-19. Phase 3 Data Points Evaluated . . . . .	5-19
Table 5-20. Overall Tracking Performance and CHR Improvement . . . . .	5-21
Table 5-21. Pilot Comments (Configuration B, Rate Limit 60, Time Delay 100) . . . . .	5-21
Table 5-22. Pilot Comments (Configuration C, Rate Limit 60, Time Delay 200) . . . . .	5-22
Table 5-23. Configuration Effect on Performance Improvement Confidence Levels . . . . .	5-24
Table 5-24. Rate Limit Effect on Tracking Performance and CHR Improvement . . . . .	5-26
Table 5-25. Pilot Comments (Configuration D, Rate Limit 15, Time Delay 0) . . . . .	5-26
Table 5-26. Time Delay Effect on CHR Improvement . . . . .	5-28
Table 5-27. Time Delay Effect on Tracking Performance . . . . .	5-29
Table 5-28. Pilot Comments (Configuration C, Rate Limit 60, Time Delay 0) . . . . .	5-29
Table B-1. Task Performance Improvement for Different Pilots . . . . .	B-35
Table B-2. Task Performance Improvement for Different Configurations . . . . .	B-36
Table B-3. Task Performance Improvement for Different Rate Limits . . . . .	B-37
Table B-4. Task Performance Improvement for Different Time Delays . . . . .	B-38
Table C-1. Flight Test Log . . . . .	C-1
Table C-2. Instrumentation Parameters . . . . .	C-21

## List of Symbols

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
$\alpha$ , alpha	Angle-of-Attack	deg
$\delta_e$ , $de$	Elevator Deflection	deg
$\delta_{eCMD}$ , $dec$	Elevator Deflection Commanded	deg
$\delta_{ef}$ , $decf$	Elevator Deflection Commanded by ROVER Filter	deg
$\theta$ , theta	Pitch Angle	deg
$\theta_t$	Pitch Angle Track Command	deg
$\omega_n$	Natural Frequency	rad/sec
$\zeta$ , zeta	Damping	--
$de_{max}$	Most Recent Maximum Commanded Elevator Deflection	deg
$de_{min}$	Most Recent Minimum Commanded Elevator Deflection	deg
$e$	Pitch Angle Track Command Error ( $\theta_t - \theta$ )	deg
$k_\alpha$	Feedback Gain (Multiplier) of Angle-of-Attack	--
$k_q$	Feedback Gain (Multiplier) of Pitch Rate	--
$q$	Pitch Rate	deg/sec
$q_{max}$	Most Recent Maximum Pitch Rate	deg/sec
$q_{min}$	Most Recent Minimum Pitch Rate	deg/sec
$s$	Laplacian Operator	rad/s
$\Delta t$	Time Difference Between $t_{de_{min}}$ and $t_{q_{max}}$	sec

## List of Symbols (cont.)

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
t_de_min	Time of de_min	sec
t_q_max	Time of q_max	sec
t_q_min	Time of q_min	sec
T	Period of q	sec

## List of Abbreviations and Acronyms

<u>Abbreviation</u>	<u>Definition</u>	<u>Unit</u>
AFIT	Air Force Institute of Technology	--
ED	Magnitude of Commanded Elevator Deflection	deg
EP	Evaluator Pilot	--
HUD	Heads-Up Display	--
MIL-HDBK	Military Handbook 1797A	--
Min_Max	Minimum_Maximum Subsystem	--
PA	Phase Angle Difference Between $q$ and $\delta_{eCMD}$	deg
PIO	Pilot-Induced Oscillation	--
PR	Magnitude of Pitch Rate	deg/sec
qF	Frequency of Pitch Rate, $q$	rad/sec
rad	Radian(s)	--
RIV	ROVER Integer Value	--
SAS	Stability Augmentation System	--
sec	Second(s)	--
SP	Safety Pilot	--
TPS	Test Pilot School	--
VISTA	Variable Stability In-flight Simulator Test Aircraft	--
VSS	Variable Stability System	--
USAF	United States Air Force	--

## Abstract

Closed loop instability caused by excess phase lag induced by actuator rate limiting has been suspected in many pilot-induced oscillations (PIOs) and oscillatory departures from controlled flight. As part of the joint Air Force Institute of Technology/Test Pilot School (AFIT/TPS) program, a longitudinal pilot command notch filter activated by a real-time oscillation verifier (ROVER) algorithm was developed to eliminate the PIO source for any developing, severe PIO.

Stick filtering performance was evaluated inside the feedback path with primary emphasis on the pilot command path. Closed loop computer simulations were conducted to prepare for the flight test. The HAVE ROVER flight test project was flown using the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA). A programmable heads-up display (HUD) was used to generate a tracking task simulating Category A fighter maneuvers. Additionally, 6 of the 12 evaluation sorties were flown against an airborne target aircraft.

Flight test results showed the stick filter was pivotal in preventing aircraft oscillatory departures and suppressing PIOS. With the original threshold settings, the ROVER algorithm correctly characterized pilot observations of the aircraft motion 72% of the time. Further analysis indicated that a high false detection rate was responsible for this relatively low correct detection rate. This result suggested that the threshold values used by ROVER to detect PIO were set too low. By varying the threshold values as part of a parametric study, a maximum overall correct detection rate of 82% was attained.

# **SUPPRESSION OF PILOT-INDUCED OSCILLATION (PIO)**

## **I. Introduction**

### **General**

The purpose of this simulation study and flight test was to attempt to eliminate oscillatory departures and/or pilot-induced oscillations (PIOs) by means of selectively attenuating pilot command in the oscillatory frequency range. While rate limiting is a major contributor to many PIOs, this study examined both rate limiting and system time delay PIO events. A more broad approach to eliminating oscillatory departures and PIOs will assist pilots in maintaining aircraft control and therefore save both lives and aircraft.

This simulation study was conducted at the Air Force Institute of Technology (AFIT), Wright-Patterson AFB, Ohio, and at the United States Air Force Test Pilot School (USAF TPS), Edwards AFB, California. The flight test project was flown in the USAF NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) aircraft (S/N 86-0048) at Edwards AFB, CA. This aircraft was maintained and operated by the Veridian Engineering, Flight Research Group, Buffalo, New York.

## Background

The Wright Brothers described pilot-induced oscillation (PIO) in the first self-propelled and piloted aircraft in the early 1900's. "The Wrights considered that the ability to 'balance and steer' an aircraft was the most challenging area of knowledge necessary for those in the aviation world" (Hodgkinson, 1999:1). The aviation industry has transitioned from pure pilot-operated, pilot-powered flight control systems to computer-commanded, hydraulically-powered control systems. Because of this transition, aircraft are now capable of handling staggering increases in air loads on the control surfaces. Additionally, many current military aircraft designs are dominated by the need for low observability. Decreasing the size of the horizontal stabilizer reduces an aircraft's observability by significantly decreasing the aircraft's radar cross section. A major drawback in this design approach is reduced aircraft stability and thus, the need for computer enhanced stability. This computer-enhanced stability is often referred to as a stability augmentation system (SAS) that "augments the natural stability of the aircraft by using feedback control" (Hodgkinson, 1999:132).

The Wright Brothers are credited with realizing that "if knowledge of stability is weak, then the control capability of the vehicle in question should be strong" (Hodgkinson, 1999:1). Even though modern aeronautical engineering has made great strides in understanding aircraft stability and control, the above concept still applies. The development of aircraft with relaxed static stability, like the F-16 Fighting Falcon, has forced the aircraft industry to develop feedback stability systems to augment the bare airframe dynamics. An unaugmented aircraft may possess longitudinal instabilities that require constant control inputs to prevent an oscillatory departure. Since pilots have

other demands on their time, computers have taken over this task of maintaining basic aircraft stability. Figure 1-1 shows a Simulink® block diagram model of an aircraft SAS feedback system using angle of attack,  $\alpha$ , and pitch rate,  $q$ , as the feedback control parameters. This inner loop SAS is enclosed by an outer, pilot control feedback loop where pitch angle,  $\theta$ , is differenced with a tracking task to generate a pilot task signal.

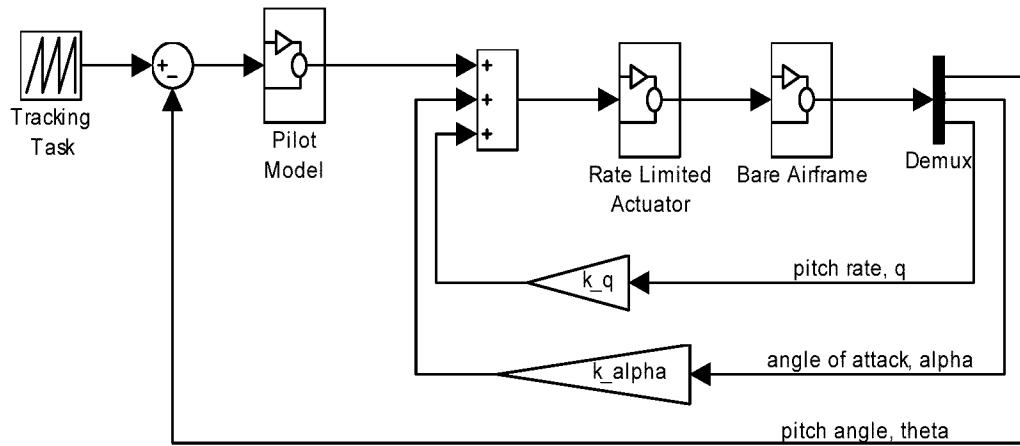


Figure 1-1. Aircraft System with a SAS

The Military Handbook 1797A defines PIO as “sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft” (MIL-HDBK, 1990:25). A 1964 NORAIR report defines a PIO as “an inadvertent sustained oscillation of the pilot-vehicle system” (Ashkenas, 1964:1). No matter the definition, most would agree that PIOs are both undesirable and a result of pilot commands. Because the causes of PIOs can be directly attributed to poor aircraft design, this author is not blaming the pilot for the PIO. However, since the pilot is an integral part of a PIO, it is reasonable to argue that a PIO could not be sustained if the pilot were effectively removed from the

aircraft command loop. This undesired aircraft-pilot coupling results when tight control is attempted and is often seen during both Category A and C type maneuvers. Category A maneuvers are “those non-terminal flight phases that require rapid maneuvering, precision tracking, or precise flight-path control” (MIL-HDBK, 1990:80). Category A maneuvers include such tasks as air-to-air combat, ground attack, weapon’s delivery, and aerial refueling. Category C maneuver are “terminal flight phases that are normally accomplished using gradual maneuvers and usually require accurate flight-path control” and include takeoff, approach, and landing (MIL-HDBK, 1990:81).

To complicate the issue of preventing PIOs, it is important to recognize that PIOs are difficult to predict, are often based on non-linear phenomena, and can “range in severity from nuisance to catastrophe” (Hodgkinson, 1999:125). Additionally, PIOs often develop rapidly and unexpected. Because of this, “it is typically not feasible for the pilot to identify and execute the required actions in real time” (McRuer, 1997:2). Furthermore, due to the adaptive nature of the human pilot and the inherent problems in modeling them mathematically, predicting PIOs is quite difficult (Anderson 1995:5).

Along with the difficulty in predicting PIOs, it is often tough to categorize them. The numerous causes of and factors involved in PIOs complicate the issue. In the 1995 Final Report, Unified PIO Theory, Volume 1, three categories of PIOs were proposed. Category I is “essentially linear and time stationary” aircraft oscillations (Klyde, 1995:96). Category II includes linear and specific series nonlinearities (e.g. rate limiting), while the Category III classification states that “complex nonlinearities are central and the closed-loop situation is often non-stationary” (Klyde, 1995:97). These

Category III PIOs are “essentially nonlinear pilot-vehicle system oscillations with transitions” (e.g. flight control system mode switching) (Klyde, 1995:17).

PIOs can have any number of contributing factors. Listed below are a few of the leading causes: “cockpit control design and control-response sensitivity, nonlinear control system phenomena, actuator rate limiting, sluggish response modes, lightly damped aircraft dynamic modes, stick sensitive gradients, unstable response modes (those not stabilized by the pilot), and unusual coupling responses” (Chapa, 1999:Ch 1, 3). Roger Hoh and David Mitchell of Hoh Aeronautics, Inc. explain that “a PIO exists when the airplane attitude, angular rate, or normal acceleration is 180 degrees out of phase with the pilot’s control inputs” (Mitchell, 1995). This phase difference between the pilot command and aircraft response is usually indicative of a fully developed PIO event.

Many organizations have focused research dollars on finding the cause of PIOs. Some researchers have focused on the pilot’s role in PIO, saying, “the most common cause of PIOs are excessive demands on the pilot” (Ashkenas 1964:17). This NORAIR report further states that the inherent human limitations of the piloted vehicle must be considered. “This is not to degrade the human pilot’s role but, instead, to emphasize it, because it is unlikely that any black-box could be devised which is as clever and effective in coping with unmanageable controlled elements as a skilled pilot” (Ashkenas, 1964:16). The bare airframe dynamics may be stable, but the excessive demands and the resulting high gains of the pilot control can drive the system unstable. Chapa quoted Duane T. McRuer’s NASA report saying, “the oscillations can therefore be identified as closed-loop instabilities of a feedback control system” (Chapa, 1999:Ch 1, 3).

One of the previously identified causes and a primary factor in many PIO studies is actuator rate limiting. Rate limiting occurs when the input rate to the control surface exceeds the hydraulic and/or mechanical capability of the control surface actuator. “With the regular use of high-gain, full-authority, fly-by-wire flight control systems, the potential for PIO [due to rate limiting] has become greater” (Mitchell, 1994:1167).

Almost all aircraft that have experienced a severe PIO have also encountered rate limiting. The Space Shuttle, YF-22, and JAS-39 Gripen are a few of these such aircraft (Mitchell, 1994:1167). Both the YF-22 and JAS-39 were destroyed as a result of a severe PIO in the pitch axis. PIOs can vary in degree from a minor nuisance caused by “a pilot overcontrolling an otherwise normal circumstance” (Mitchell, 1994:1167) to “large amplitude, potentially catastrophic oscillations” (Klyde, 1995:15). Klyde has identified the latter as a severe PIO.

Rate limiting has been identified as a contributor to PIOs for two main reasons. First, it introduces additional phase lag between commanded control surface position ( $\delta_{eCMD}$ ) and actual control surface position ( $\delta_e$ ). Second, during rate limiting, the response to the pilot’s input is attenuated by this nonlinear event. One obvious solution is to attempt to improve actuator performance by raising the rate limit. This increased rate limit would require larger and heavier actuators. McDonnell Douglas found that for the YF-23, the aircraft was still PIO susceptible with an actuator rate limit of 135 deg/sec (Buckley, 1995). By comparison, F-16 era aircraft generally utilize actuators capable of a rate of 60 deg/sec. Since some modern aircraft are designed with output feedback control systems stabilizing the unstable bare airframe, the elevator must respond to both computer SAS inputs as well as pilot-commanded inputs. “Under limiting conditions, the

[flight control system] can sometimes remove the pilot from direct access to the control effectors in order to execute" the stabilizing functions (McRuer, 1997:48). Therefore, aggressive maneuvering can exceed the actuator rate limit resulting in degradation toward unaugmented/open loop aircraft dynamics.

## Objectives

The primary objective of this study was to develop a real-time logic switch and filter to detect and suppress undesirable oscillatory dynamics thus eliminating longitudinal oscillatory departures and/or PIOS. The specific objectives were:

1. To improve and implement an existing *real-time* oscillation detection algorithm into both ground and flight simulations,
2. To investigate the performance of the detection algorithm in concert with a notch filter on pilot's longitudinal commands of highly augmented fighter aircraft flight control systems,
3. To investigate the performance of the detection algorithm and filter on the handling qualities of an unaugmented fighter flight control system, and
4. To obtain flight test data to assist others in the study of pilot-induced oscillations and/or longitudinal oscillatory departures.

This investigation was performed in two parts. The first part was a simulation study to determine the feasibility of using the PIO detection algorithm as a switch to activate a notch filter on pilot commands. These results helped shape the second part, a flight test project that implemented both active filtering and visible notification to the

pilot of filter activation. The flight test evaluated the concepts developed during the ground simulation study.

## **Approach**

The following steps were accomplished for this project:

1. Analyzed an existing oscillation detection algorithm:
  - A. To investigate the algorithm's adaptability to operate real-time
  - B. To modify the algorithm to run real-time during simulation
2. Used the HAVE FILTER aircraft simulation configurations:
  - A. To verify aircraft configuration dynamics
  - B. To verify aircraft responses through simulation
3. Incorporated the oscillation detection algorithm:
  - A. To create a signal parameter identifier to determine minimum and maximum values and the associated times at these extreme points
  - B. By incorporating a smoothing filter to eliminate noise (required during ground simulation and flight test)
4. Developed a notch filter to attenuate longitudinal pilot commands:
  - A. By creating a second-order Butterworth notch filter centered in the PIO frequency range
  - B. By testing the filter for various potential pilot commanded inputs
  - C. To verify that low frequency pilot commands were not attenuated while the filter was active

5. Studied PIO development due to actuator rate limiting and excessive equivalent system time delay:
  - A. By incorporating both the oscillation detector and notch filter into the aircraft simulation model
  - B. By running numerous trials of four aircraft configurations with the filter actively engaging when a PIO was detected
  - C. By running numerous trials of four aircraft configurations with an active filter suppressing PIOs due to excessive system time delay
6. Determined configurations for use during the flight test portion based on simulation data and the results of the HAVE FILTER project
7. Conducted the flight test project in a variable stability aircraft.

## **Scope**

This research project was limited in scope. Some of the constraints and factors driving the limitations are listed below:

1. The study focused exclusively on the longitudinal/pitch axis,
2. Tracking tasks were limited in nature but representative of Category A fighter maneuvers during aerial combat,
3. Aircraft configurations were limited to a select few bare airframe dynamics, rate limits, and time delays, and
4. Flight test time was limited to 12 VISTA NF-16D sorties (approximately 16 hours), as per the TPS budget.

## II. Theory

This chapter specifies the details of this pilot-induced oscillation (PIO) suppression project. Additionally, the dynamics of the notch filter, aircraft model, and actuators will be discussed. The specifics of PIO detection and the Real-time Oscillation VERifier (ROVER) will be examined in this chapter. This chapter concludes with a discussion of the chosen pilot model, noise simulation, and the Variable Stability In-flight Simulator Test Aircraft (VISTA) model.

### **PIO Detection and Suppression**

Once a serious flying qualities deficiency is identified, it is incumbent upon the aircraft designers to remedy the situation. Otherwise, that aircraft might never find a viable market. During free-flight number 5, after being released from a NASA 747, the Space Shuttle made a gliding approach to the main runway at Edwards AFB, CA. During the flare for touchdown, the orbiter experienced a severe PIO resulting in several firm touchdowns and an extremely long landing. Following this landing phase PIO, NASA investigated possible solutions to this handling qualities deficiency. “This proneness [of the Space Shuttle] to PIO has been attributed to a number of factors, the most important being excessive control system time delay” (Shafer, 1984:1). The most desirable course of action would be to “redesign the control system, correcting these deficiencies. However, it is not always possible to do so in a timely manner, in part because of the extensive validation and verification process required for these control systems” (Shafer, 1984:1). A design group can investigate indirect solutions to improve flying qualities by

means of adaptive filters. “The filter can potentially suppress pilot-induced oscillations and prevent actuator rate limiting” by adjusting the pilot’s available command to the control surface as a function of the frequency and amplitude of his input (Bailey, 1981:2).

NASA tested several suppression filters during the early 1980’s. Using a suppression filter, “complete control of the aircraft is retained until the pilot control inputs approach those which are ‘known’ to induce oscillations. When this condition occurs, the filter reduces the pilot’s command gain to the control surfaces, thus minimizing the resultant aircraft motion. The filter, in essence, opens the pilot/vehicle control loop to suppress the PIO” (Bailey, 1981:2). This opening of the pilot control loop can only be tolerated if the resulting aircraft motion is preferable to the unfiltered, closed loop motion. For instance, few pilots would consent to a filter breaking this pilot control loop during a landing task if it meant losing longitudinal control of the aircraft. Certainly a filter on pilot commands must be used judiciously. “The results [of these NASA tests] showed that the average Cooper-Harper ratings were improved by this filtering” (Shafer, 1984:4).

“Various configurations of the PIO suppression filter were evaluated in the flight programs, and most of the filter configurations reduced the occurrences of PIOS and improved the handling qualities of the PIO-prone aircraft” (Shafer, 1984:1). One drawback of this type of suppression filter is that they are always active and therefore can create phase distortion in the command path. “Suppression filters … attenuate [pilot] commands and add phase lag to the aircraft response, degrading general handling qualities, especially for high bandwidth tasks” (Leggett, 1999:6). A proposed solution to this drawback is to activate the suppression filter only when the oscillatory event is

occurring. In this case, the slight phase distortion introduced by the filter would be more desirable than the ensuing PIO. “The success with PIO suppression filters for the Space Shuttle made it likely that such techniques could be applied to other classes of aircraft, such as high-performance fighters” (Shafer, 1984:1).

### **Real-time Oscillation VERifier (ROVER) Development**

Mitchell’s research at Hoh Aeronautics, Inc. led to the development of a PIO detection algorithm called ROVER (see Appendix A). In essence, ROVER is an aircraft motion, oscillation detector. ROVER analyzes both pilot commanded elevator deflection,  $\delta_{eCMD}$ , and aircraft pitch rate,  $q$ . Historical data shows that all severe PIOS have occurred in the frequency range of one to eight radians per second (Mitchell, 1999). Additionally, an indication of a developing PIO is an increasing phase angle disparity between the pilot command and actual aircraft performance. ROVER analyzes a given aircraft oscillation and assigns a numerical value of severity based on the following four conditions:

- The first is the magnitude of the aircraft pitch rate,  $q$ . Only significantly large aircraft oscillations will be classified as a severe PIO.
- Secondly, only motions resulting from significantly large pilot commands,  $\delta_{eCMD}$ , will be characterized as severe.
- Thirdly, the algorithm considers only sizeable phase angle differences as measured between  $\delta_{eCMD}$  and  $q$ .
- Lastly, the algorithm only considers oscillations in the one to eight radians per second frequency range as satisfying the fourth and final condition.

ROVER analyzes each condition separately and assigns an integer value of one or zero (true or false) to each of the above conditions. Only a ROVER value of four is considered a severe PIO (i.e. all four conditions are true).

The condition statements above purposely contain the vague phrases “significantly large” and “sizeable” to indicate these parameters are likely aircraft dependent. It is reasonable to expect that a level 1 bare airframe would have better open and closed loop dynamics than a level 3 bare airframe. Therefore, it is equally reasonable to alter the condition thresholds needed to identify undesirable and severe oscillations. If the thresholds were set too low for a given aircraft configuration, then nuisance warnings and activations of the filter would be probable. A worse situation, though, would be setting the thresholds too high for a PIO-prone configuration. In this situation, the detector may not identify the oscillation as being severe and would make no attempt to suppress a developing PIO. Thus, it is possible for an unstable bare airframe to depart controlled flight prior to reaching arbitrarily high thresholds.

The thresholds set on the magnitude of  $\delta_{eCMD}$  and  $q$  prevent small magnitude oscillations, motion that might occur in an everyday close formation flight, from being registered as a severe PIO. The ROVER system is versatile in that it can be adjusted to a given configuration, but its internal logic still looks to meet the four necessary and sufficient conditions to categorize an aircraft oscillation as a severe PIO:

- magnitude of the aircraft pitch rate (PR),
- magnitude of the pilot commanded elevator deflection (ED),
- phase angle (PA) difference between  $\delta_{eCMD}$  and  $q$ , and
- frequency of aircraft pitch rate (qF).

## Notch Filter Development

Notch filters are currently incorporated in aircraft designs to eliminate various vibrational modes. “Typically the frequency of the notch is designed to cancel a known resonance, particularly those due to structural vibration modes. Ideally, if the notch perfectly cancels the structural resonance, we see no net effect” (Hodgkinson, 1999:144). The idea of a notch filter on pilot commands is to eliminate a required element in a sustained PIO. “Ideally, complete control authority is retained by the pilot unless the pilot’s control inputs approach those known to induce oscillations through pilot-aircraft coupling. Essentially, the filter reduces the gain in the pilot-aircraft control loop, circumventing flying qualities problems caused by that loop” (Shafer, 1984:2).

“In calling them pilot-induced oscillations, engineers are referring to the fact that the oscillations disappear as the pilot relinquishes control of the aircraft” (Hodgkinson, 1999:125). If a pilot is unable to relinquish control (e.g. in close proximity to the ground) or is unaware of a developing PIO, then a notch filter can attenuate pilot inputs in the critical frequency range while still allowing unattenuated command at very low frequencies. The notch filter in this project operates much like a low pass filter. Even while the filter is active, the pilot retains low frequency authority of the aircraft. Figure 2-1 shows a Bode plot of this notch filter. The notch filter transfer function is:

$$\frac{\delta_{eFiltered}(s)}{\delta_{eCommand}(s)} = \frac{(s + 2.5)^2(s + 8)^2}{(s + 0.6)^2(s + 33)^2} \quad (1)$$

The most critical elements of this magnitude plot include 90% attenuation near 3.5 rad/sec and unattenuated command authority at low frequency. This filter is not continuously active, but rather it is activated only when a severe PIO is detected.

Therefore, it does not induce phase distortion throughout the simulation. Previous flight tests have used “adaptive, nonlinear filters that reduce the pilot’s control authority when conditions signaling an incipient PIO [were] evident” (Shafer, 1984:1). “One [such] filter used the estimated frequency of the pilot’s control inputs, derived from pitch-stick position, to determine the onset of PIO. Another used the rate of the pilot’s control inputs to determine the onset of PIO” (Shafer, 1984:2). Both of these suppression filters were continuously active and could potentially induce phase distortion. This project only activates the notch filter when the conditions are met to categorize the aircraft oscillation as a severe PIO (a ROVER value of four).

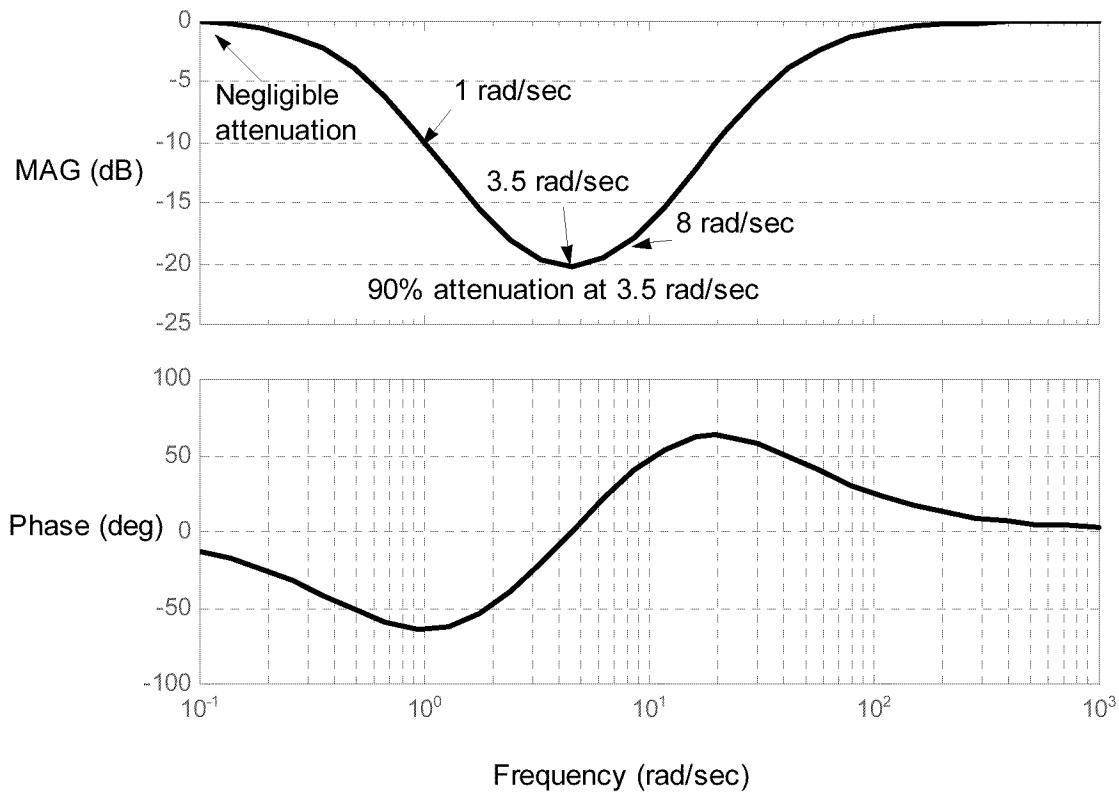


Figure 2-1. Notch Filter Bode Diagrams

## Aircraft Model Development

The four Simulink® aircraft models developed mirror the work done by Mike Chapa in the HAVE FILTER flight test program during the fall of 1998. The Case A aircraft has no stability augmentation. This configuration has bare airframe dynamics that display good handling qualities and is therefore considered level 1 (see Figure 2-2). Case B has a bare airframe that is acceptable/level 2 with only a small amount of stability augmentation needed to bring it to level 1 closed loop. Case C is a poor/level 3 bare airframe with a moderate amount of stability augmentation required to bring it to level 1. Case D is an unstable/unacceptable bare airframe requiring a significant amount of stability augmentation to bring it to level 1 closed loop (Liebst, 1999:2). Each consecutive bare airframe (from Case A to D) exhibits decreasing stability. However, the SAS feedback (see Figure 1-1) has been designed to provide identical closed loop dynamics for all four configurations. Each aircraft's closed loop poles lie in the *sweet spot* of level 1 handling qualities. Figure 2-2 shows the locations of the bare airframe configurations (open loop dynamics) as a function of short period damping and natural frequency. The closed loop poles for all four cases plot at point A.

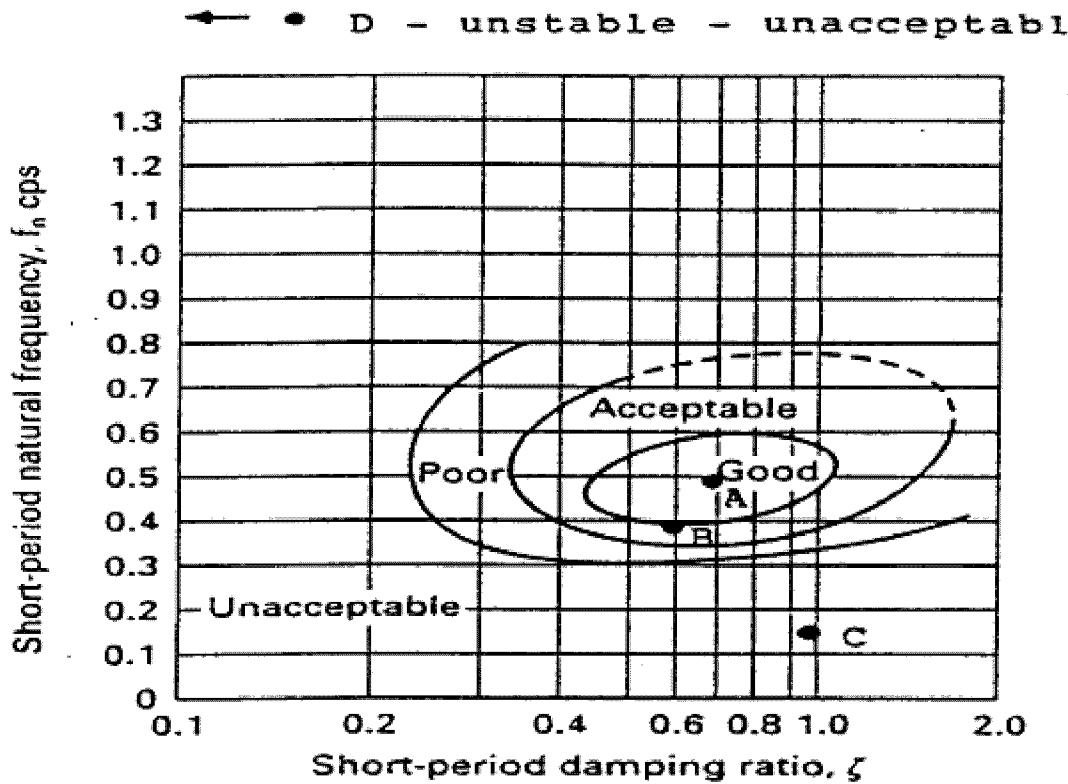


Figure 2-2. Short Period Handling Qualities (Liebst, 1999:5 and O'Hara, 1967)

Table 2-1 contains bare airframe pole coordinates as well as the closed loop poles. These bare airframe poles become important when that aircraft model reaches a nonlinear saturation. “In systems involving a displacement saturation nonlinearity in the forward loop, when the saturation occurs, the closed loop system effectively becomes open loop” (Liebst, 1999:2). The configurations with little or no augmentation feedback should be less prone to PIO due to their more stable bare airframe dynamics. Conversely, Cases C and D are prone not only to PIO, but also can potentially depart controlled flight if rate limiting is encountered. The thrust of this project centered on the Case C and Case D aircraft configurations.

Table 2-1. Aircraft Configurations and Feedback Gains

Case	Bare Airframe Poles (Open Loop)	$K_q$	$K_\alpha$	A/C poles with SAS (Closed Loop)
A	$-2.20 \pm 2.22 i$	0	0	$-2.20 \pm 2.22 i$
	$-0.017 \pm 0.074 i$			$-0.017 \pm 0.074 i$
B	$-1.42 \pm 1.86 i$	0.14	0.21	$-2.20 \pm 2.22 i$
	$-0.016 \pm 0.079 i$			$-0.0166 \pm 0.0736 i$
C	$-0.86 \pm 0.084 i$	0.24	0.51	$-2.196 \pm 2.227 i$
	$-0.009 \pm 0.097 i$			$-0.0168 \pm 0.0737 i$
D	-1.67	0.34	0.61	$-2.20 \pm 2.22 i$
	$-0.017 \pm 0.033 i$			$-0.0169 \pm 0.0737 i$
	+1.07			

In order to accurately model both position and rate saturation, the following actuator model was incorporated into the aircraft system (see Figure 2-3). This actuator subsystem provides the opportunity to control the rate and position saturation values independently. For small amplitude inputs, the actuator has the following dynamics:

$$\frac{\delta_{eCMD}(s)}{\delta_e(s)} = \frac{20}{s + 20} \quad (2)$$

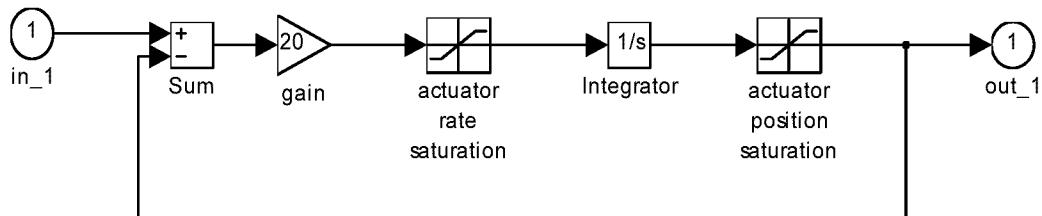


Figure 2-3. Actuator Dynamics with Saturation

## Pilot Model Development

The primary task in this project was to develop an aircraft system that would exhibit PIO and then to validate the operation of the ROVER PIO detection system and notch filter. With this in mind, the pilot model chosen was a simple proportional gain and delay model with the following dynamics:

$$Y_p(s) = K_p * e^{-\tau s} \quad (3)$$

where  $K_p$  is the pilot gain and  $\tau$  is the associated time delay. In Figure 58 of the MIL-HDBK, “Simplified Pilot-Vehicle Closure for Pitch Control”, this type of modeling is labeled an idealized pilot (MIL-HDBK, 1990:227). “Regardless of the pilot model chosen, it is still a model and cannot define a human being in all circumstances at all times and is therefore a limitation” (Liebst, 1999:2). While this pilot model may appear too simplistic, this type of pilot model is used in determining various other handling qualities parameters, including the Hoh Bandwidth Criterion (MIL-HDBK, 1990:227). Later, it will be shown that this pilot model is adequate to cause a PIO and is therefore appropriate for this project.

## Stick and Feedback Noise

Due to the real world nature of gyroscopes, accelerometers, and angle of attack probes and transducers, it is unreasonable to expect a pure signal transmitted through the feedback channels. Most measured aircraft motion signals have a small level of noise, if due only to the nearly imperceptible aerodynamic aircraft vibration. “Internal noise proved to be a significant factor in previous pre-filter studies” (Chapa, 1999:Ch2, 12). Since the ROVER switching logic is sensitive to noise, a noise-suppression filter was

incorporated into the model. Specifics of this noise filter are presented in the next chapter. During simulation, a band-limited, normally distributed white noise, with an RMS of up to ten percent of the signal magnitude, was used. Based on engineering judgment, the guidance of the Veridian Flight Research Group engineers, and the sample signal provided by Veridian and generated by VISTA during an actual flight, a ten percent noise signal exceeds the noise values expected for this flight test project (see Figure 2-4). This figure shows a fairly clean signal with a noise level less than five percent of the actual pitch rate value.

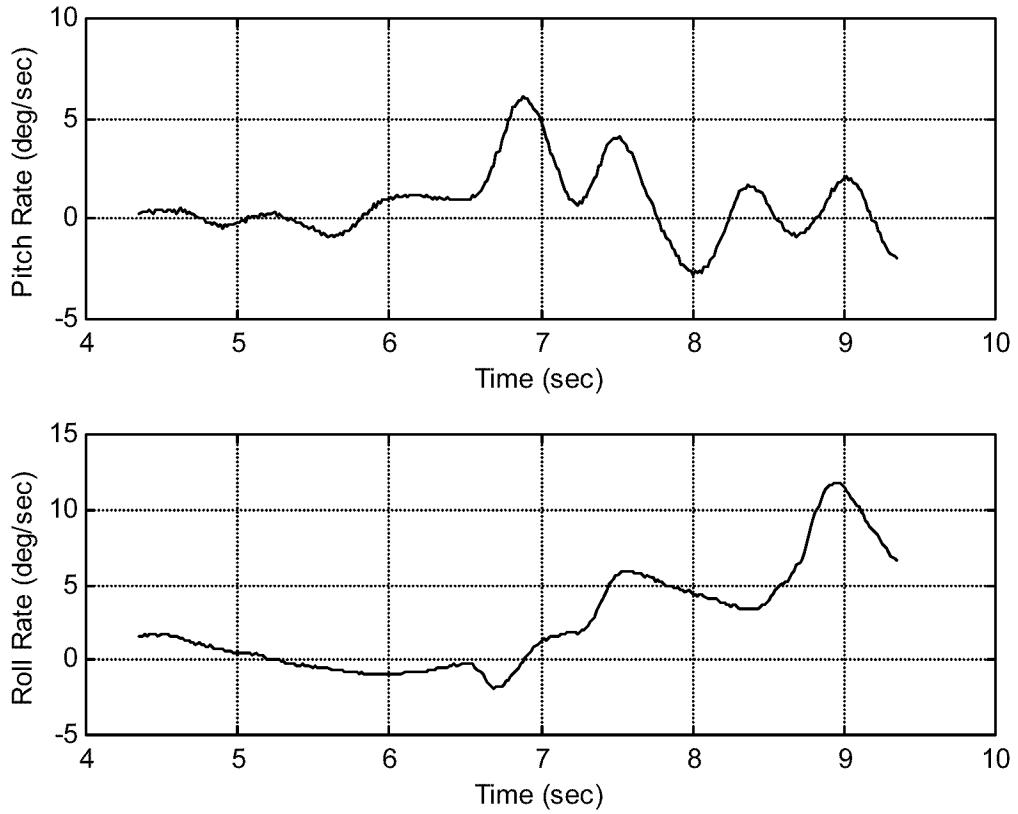


Figure 2-4. VISTA Sample Data and Associated Noise Levels

## VISTA Aircraft Model

The following figures provided by Veridian Engineering, Flight Research Group show the Simulink® diagrams of the VISTA aircraft incorporating the variable stability system (VSS) logic (see Figures 2-5 and 2-6).

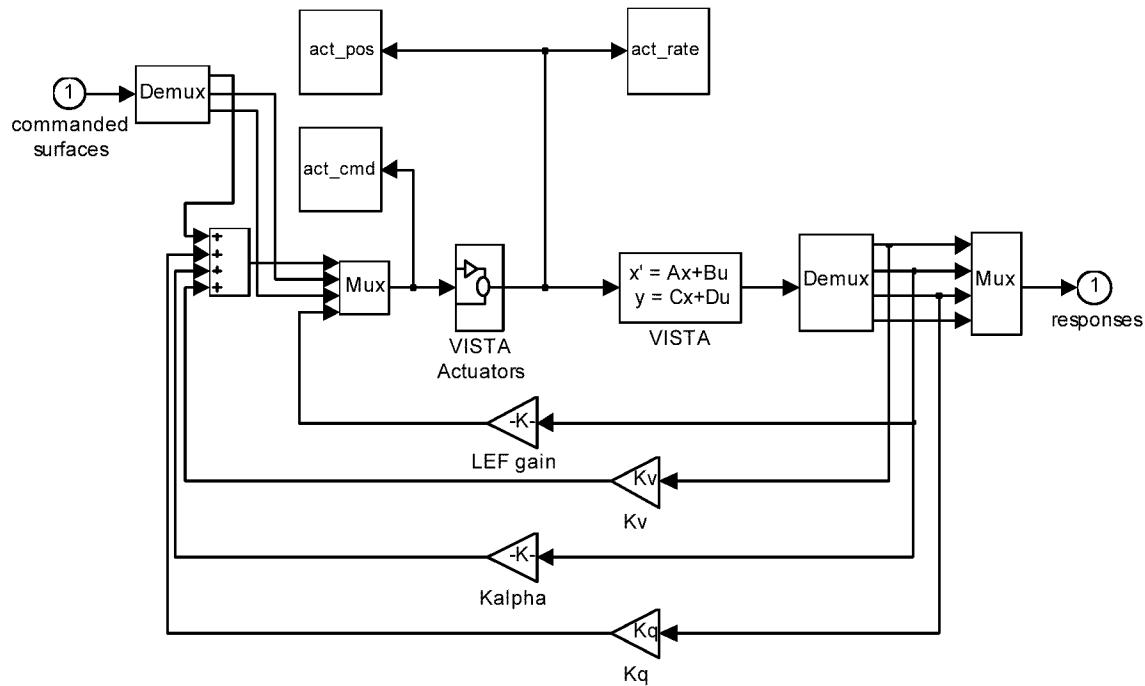


Figure 2-5. Variable Stability System (VSS) Architecture

The key feature of Figures 2-5 and 2-6 is that VISTA incorporates a model following scheme whereby a pilot's command is analyzed within the VSS. The simulated aircraft response is determined via a math model, and then an actual command is sent to the NF-16D's digital flight control system to force the VISTA to respond as the simulated airframe would. In order to make it fly and react like another aircraft, multiple commands are sent to the elevons and leading edge flaps of the VISTA F-16. Figure 2-5

shows the block diagram for the VSS and its associated feedback loops. Figure 2-6 shows a larger picture of the VSS architecture that includes the model following feedback loop. The dashed box in Figure 2-6 is a simplified diagram of the entire Figure 2-5. Figure 2-6 further details a variable feel stick influence on the VSS system. The stick dynamics are a critical portion of the simulation as poor stick dynamics can induce poor handling qualities in an otherwise good flying aircraft.

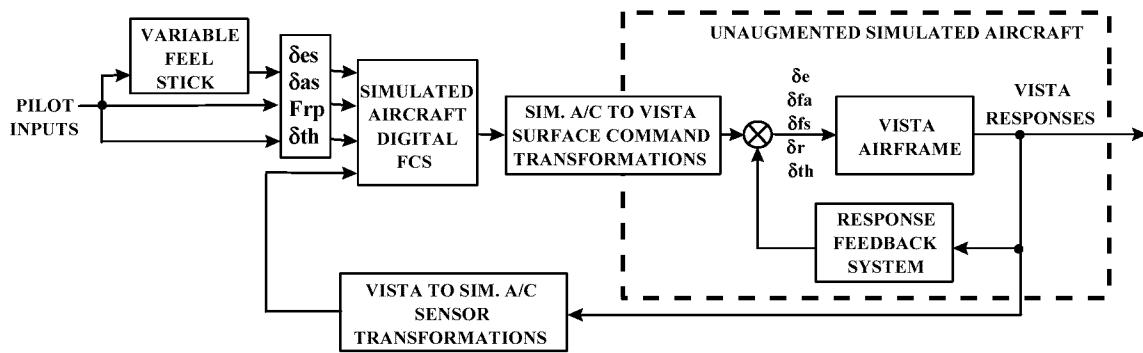


Figure 2-6. VISTA Model Following Architecture

### III. ROVER and Notch Filter Simulation Results

Computer simulations are presented in this chapter. Matlab® and Simulink® computer programs were used to develop and analyze aircraft configurations and to implement the Real-time Oscillation VERifier (ROVER). Computer simulation trials included: 1) continuous simulation using four variations of bare airframe dynamics and associated gains within the SAS feedback loop, 2) various input tracking tasks with and without the ROVER algorithm and notch filter active, and 3) variations of actuator rate and position saturations and equivalent system delay values to produce PIO-prone configurations. The following Simulink® results are based on a fixed time step integration parameter equal to 100 Hertz. Throughout the remainder of this report, any reference to pitch rate,  $q$  (positive is nose up), is presented in deg/sec. Additionally, elevator deflection,  $\delta_e$  (positive is elevator trailing edge down), and commanded elevator deflection,  $\delta_{eCMD}$ , are presented in deg. Pitch angle, theta ( $\theta$ ), is also in deg.

#### Continuous Simulation

This ROVER simulation developed several aircraft configurations, imposed various conditions to drive each configuration into a PIO condition, and implemented the ROVER PIO detector and notch filter on pilot commands to the elevator. As discussed previously, the pilot model chosen was simplistic. However, based on the objectives of this research, the simple proportional gain and delay pilot model proved quite effective:

$$Y_p(s) = K_p * e^{-\tau s} \quad (4)$$

where  $K_p$  was 0.17 and  $\tau$  was 0.25 seconds.

The aircraft system was driven by a tracking error signal,  $e$ , generated from the difference between the instantaneous aircraft pitch angle,  $\theta$ , and the theta tracking task. Figure 3-1 shows this theta feedback system with the ROVER subsystem inserted directly following the pilot model transfer function.

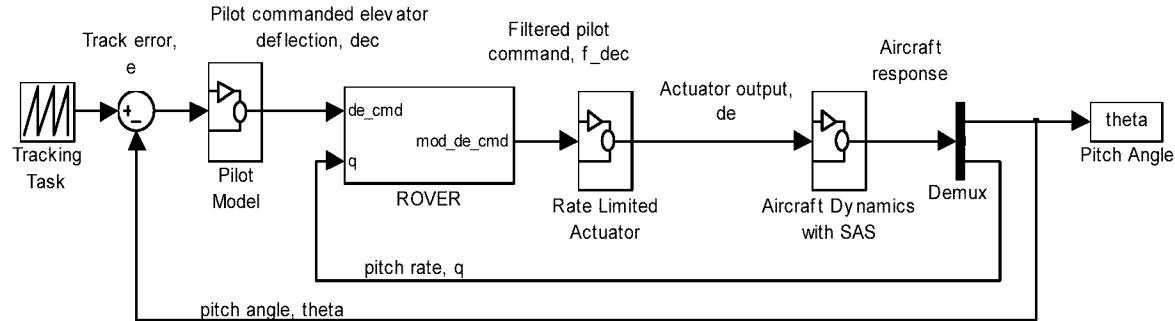


Figure 3-1. Aircraft System Driven by Theta Track Error

Because the primary objective of this project was to produce a PIO event within each configuration, the vast majority of simulation trials merely used a step input as the tracking task (see Figure 3-2). More complex tracking tasks would also produce the desired result, but a simple step input was easier to implement and analyze. Various signal amplitudes were investigated. Values ranged from less than 5 degrees up to and including 50 degrees. The majority of configurations, however, required amplitudes greater than 15 degrees in order to induce the desired aircraft response. In every case of aircraft oscillation, PIO, or oscillatory departure, the aircraft response was driven by the pilot attempting to return the aircraft to straight and level flight. After the initial command of the step input, the task was essentially a zero tracking task signal (i.e. the pilot must attempt to track the horizon).

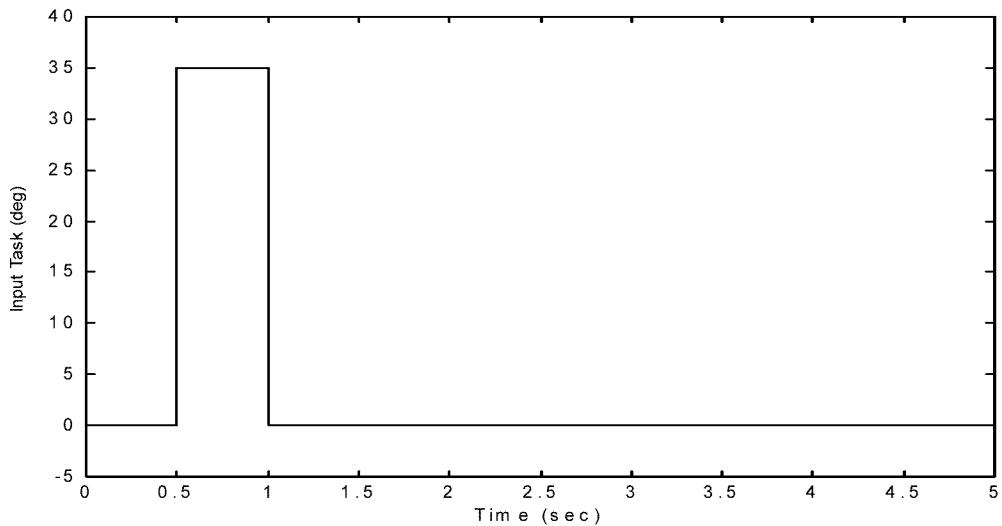


Figure 3-2. Step Input with 35 deg Amplitude and 0.5 sec Duration

### Bare Airframe Configurations

Chapter 2 laid the foundation for the development and choice of bare airframe dynamics. Each simulation model used a SAS similar to Figure 1-1 and a theta tracking task driver (see Figure 3-1). Table 2-1 contains a listing of both open and closed loop pole locations for the low order equivalent systems. Unless specifically detailed otherwise, all simulation trials operated with a standard elevator rate limit of 60 deg/sec and a deflection, or position saturation, of 35 deg. Figure 3-3 shows each aircraft configuration response to a 35 degree step input tracking task without any filtering of  $\delta_{eCMD}$ . In order to simplify the plots, the negative of  $\delta_{eCMD}$  was plotted to illustrate the reactive nature of the  $q$  response. While both Case A and B display oscillatory motion after the tracking task has returned to zero, neither develops into a PIO. Case C, on the other hand, does develop into a PIO while the pilot attempts to return the aircraft to level flight. Due to the location of the open loop poles, this configuration becomes neutrally

stable in the presence of elevator rate saturation. This elevator rate and position saturation is indicated by the sawtooth pattern of the elevator command (see Case C of Figure 3-4 below).

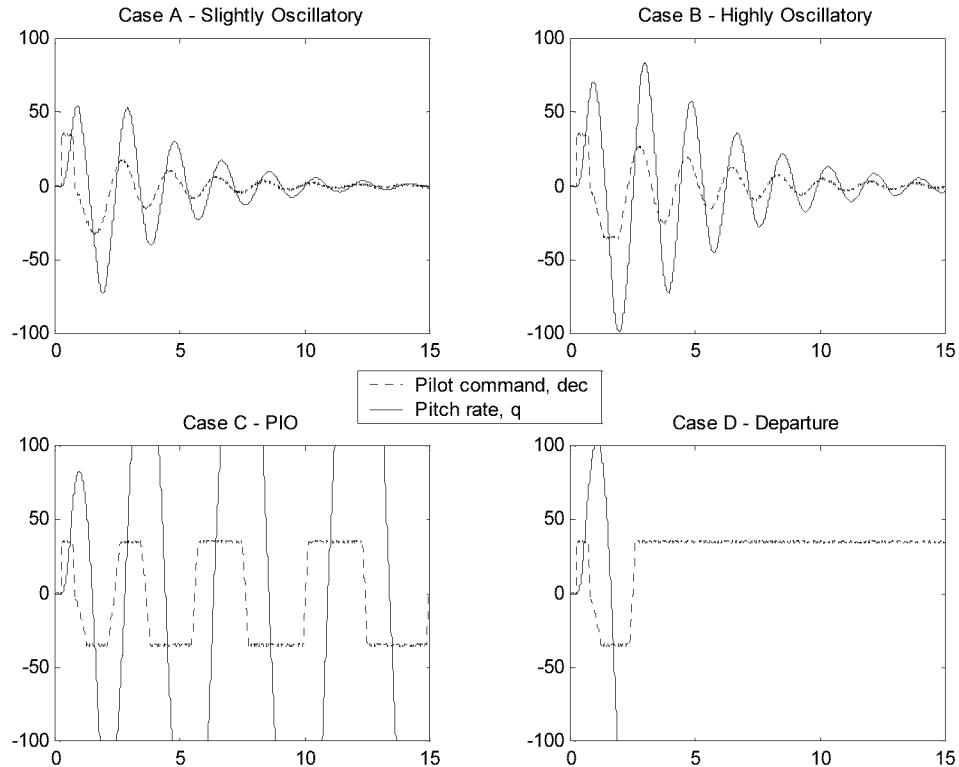


Figure 3-3. Aircraft Response to a 35 deg Step Input

Under the standard conditions for rate and position saturations, neither Case A nor B would develop into a PIO for any step inputs with amplitudes up to 50 degrees. Case C, with open loop poles very near the origin, could be driven into a PIO with step amplitudes greater than 18 degrees. With a right half plane open loop pole, Case D could not be driven to PIO. Instead, it would display instability and depart controlled flight for any tracking tasks greater than 14.5 degrees (see Figure 3-3, bottom right graph).

## **ROVER Implementation**

As discussed in Chapter 2, the basic concept of ROVER detecting a severe PIO is that four specific conditions, or thresholds, must be met by the aircraft and pilot. The four individual conditions are:

- magnitude of aircraft pitch rate (PR),
- magnitude of commanded elevator deflection (ED),
- phase angle (PA) difference between  $q$  and  $\delta_{eCMD}$ , and
- frequency of  $q$  ( $qF$ ).

Each of the four conditions has a switch in this Simulink<sup>®</sup> model. Each condition has a threshold that is variable. If the calculated value going to each switch equals or exceeds the threshold for that switch, then the condition is met and a one, or true response, is sent as an output. The PIO Severity Logic system in Figure 3-4 then sums these integers to determine the overall ROVER value. This value is called the ROVER integer value (RIV).

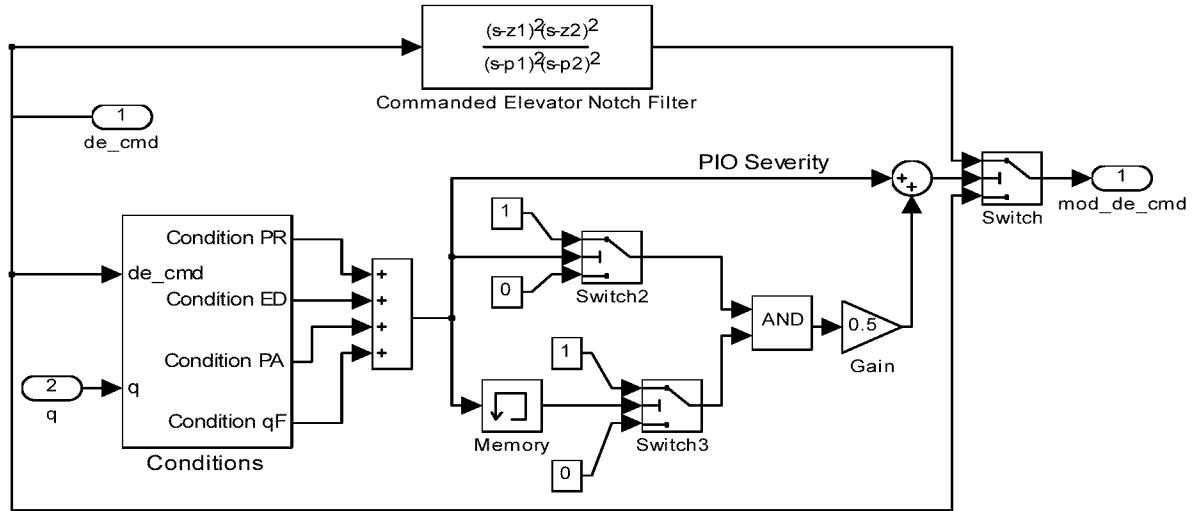


Figure 3-4. PIO Severity Logic

PIO Severity Logic. The above diagram details the Simulink® logic for switching between an unattenuated pilot command signal and one that has been modified by the notch filter (see Figure 2-1 for the notch filter Bode diagram). The specifics of the Conditions block are discussed in the next section. The output from that subsystem is used by this PIO Severity Logic system as an input into a summing block and sent directly to the switch block with a threshold of four. If the PIO severity signal is a four, then the switch only allows the filtered pilot command to pass out of this subsystem. The instant when all four conditions are met and the RIV is a four is called a ROVER activation.

The internal logic of this subsystem compares both the current and previous ROVER values. In the event that both are three or higher, it then adds one half to the current value. While this increased value was not used during ground simulation, it could be used in flight to signal the pilot of a condition approaching a severe PIO. The idea is

that if ROVER establishes two consecutive values of three, resulting in a ROVER value of 3.5, then the pilot should be warned of impending PIO. The pilot may then be able to modify the control inputs to suppress the oscillation prior to a ROVER activation. This potentially avoids the ROVER activation and eliminates the need to filter the pilot's commands. This is predicated on the fact that the pilot is effectively warned of the situation. Essentially, the pilot can open the tracking loop, or simply reduce his gain during that portion of the tracking task to prevent the aircraft from proceeding into a severe PIO.

Looking at Figure 3-4, one can see that the only two inputs to this system are  $q$  and  $\delta_{eCMD}$ , while the single output parameter is  $\delta_{eCMD}$  (labeled mod\_de\_cmd for clarity). While this system, along with the lower level subsystems, does modify and filter the original  $q$  and  $\delta_{eCMD}$  signals internally to facilitate signal comparison, only the pilot command actually passes from this block. In most cases, the unattenuated/unfiltered pilot commanded signal is sent to the aircraft actuator. However, when ROVER determines the pilot-aircraft system is developing into a severe PIO (by referencing a RIV of four), the pilot commanded signal is then filtered and the attenuated signal is passed.

ROVER Conditions Subsystem. The next level within this ROVER system is the Conditions Subsystem (see Figure 3-5). This block accepts  $q$  and  $\delta_{eCMD}$  as inputs and produces integer values of one or zero corresponding to each of the four ROVER conditions. The ROVER Conditions Subsystem calls another lower level subsystem in order to determine the appropriate values for each of the four conditions. The lowest level subsystem is the Minimum\_Maximum (Min\_Max) Subsystem discussed in the next section. The Conditions Subsystem passes  $q$  and  $\delta_{eCMD}$  to Min\_Max and uses its seven

output values to determine the individual conditions. The seven signal parameters produced within Min\_Max are the current values for: maximum and minimum  $q$  ( $q_{max}$  &  $q_{min}$ ), maximum and minimum  $\delta_{eCMD}$  ( $de_{max}$  &  $de_{min}$ ), time that  $q$  reached its most recent maximum and minimum ( $t_{q_{max}}$  &  $t_{q_{min}}$ ), and the time when  $\delta_{eCMD}$  reached its most recent minimum ( $t_{de_{min}}$ ).

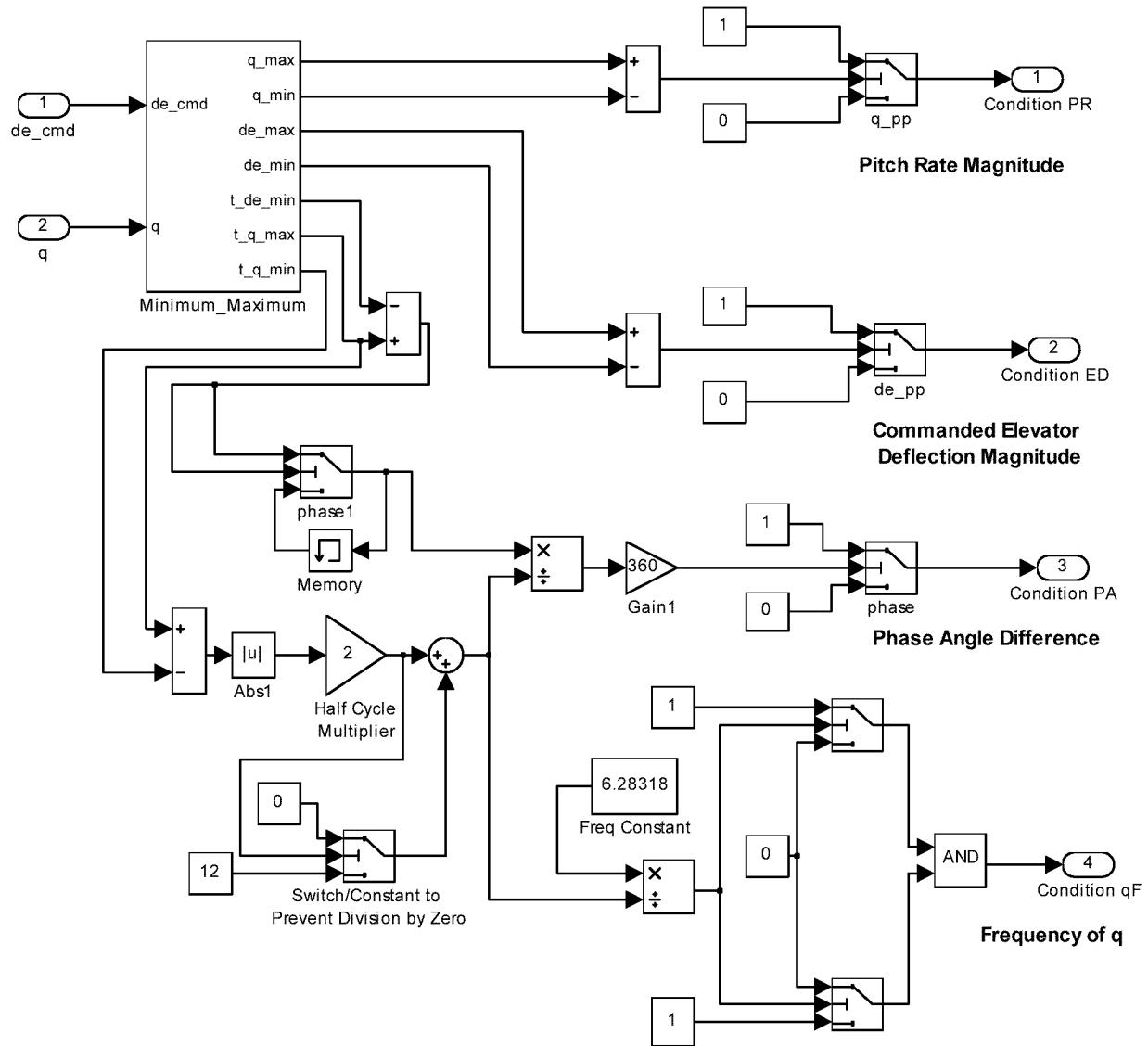


Figure 3-5. ROVER Conditions Subsystem

The pitch rate magnitude (PR) condition determines the value of the current pitch rate by differencing the current maximum and minimum values. The threshold for PR is adjustable but was set at 12 deg/sec for this project. The commanded elevator deflection magnitude (ED) is calculated in the same way using  $\delta_{eCMD}$  and had a threshold of 5 deg. These two conditions allow small aircraft responses and pilot commands to be ignored by the ROVER logic. For instance, the small oscillations often encountered while flying in close formation or during precise glideslope adjustments will not be categorized as a severe PIO due to the small magnitudes of  $q$  and  $\delta_{eCMD}$ . These two conditions necessitate the requirement for not only large amplitude aircraft motion, but also verify the motion was due to a significantly large pilot input. Mitchell determined the values for these thresholds after years of PIO investigation and research. His research revealed that historically, all severe PIO events exceeded these values (Mitchell, 1994).

The third condition is the phase angle difference (PA) between the pilot and the aircraft. This portion of the Conditions Subsystem differences the time at which  $q$  and  $\delta_{eCMD}$  reached their individual maximums. This difference is  $\Delta t$  and represents the time lag in aircraft response to a pilot command. Because the sign convention for a positive elevator deflection would induce a negative aircraft response (positive  $\delta_{eCMD}$  generates a negative pitch rate),  $t_{q\_max}$  is differenced with  $t_{de\_min}$ . The time difference between when the pilot command is at a peak and when the aircraft motion reaches its peak is the time lag of interest. An aircraft response that stays in phase with pilot command is not a PIO, but rather it is a highly desirable trait. This PA condition is met only when the pitch rate gets out of phase with the pilot's command (i.e. pitch rate is lagging too far behind the pilot command). The phase angle difference is determined by the following equation:

$$PA = \frac{\Delta t}{T} * 360 \quad (5)$$

where T is the period of the aircraft pitch oscillation (the period of the q motion). T is calculated from a half cycle of q by differencing the t\_q\_max and t\_q\_min values and multiplying the result by a factor of two. The 360 multiplier (seen in the middle of Figure 3-5) simply converts the phase angle difference into an angle measure in deg.

Based on historical data, Mitchell determined a value of at least 75 deg should be used as the threshold for PA (Mitchell, 1994). During the Simulink® simulation process, slightly different threshold values were determined. These thresholds were a function of bare airframe dynamics. In order to avoid nuisance activations of the notch filter, a high value must be chosen for both stable and unstable bare airframes. However, a threshold set too high could result in no ROVER activations for actual PIOs. Since Case A and B configurations could not be driven to PIO with the standard 60 deg/sec rate limit, their steady state phase angle difference was investigated. Due to normally occurring delays within any aircraft system, the aircraft response will always lag behind the command input. Multiple trials of these stable configurations revealed a normal phase lag of up to 60 deg during non-PIO responses. For this reason, a 65 deg phase angle threshold was chosen for any stable bare airframe configuration.

By a similar analysis, the unstable bare airframe configuration was determined to need a lower PA threshold. Due to the unstable nature of Case D in the presence of rate limiting, this lower PA threshold was required in order to prevent oscillatory departure. Often this configuration would depart controlled flight within the first two to three seconds of simulation. During these trials, the PA was observed increasing but often did

not exceed 65 deg prior to an oscillatory departure. For this reason, the PA could not be allowed to grow to such a large value prior to attempting to correct this undesired motion. While the PA value would often eventually exceed the higher threshold, it was too late to prevent the oscillatory departure. A lower threshold on PA not only allowed for normal, desired aircraft motion and tracking of most tasks, but it also offered the opportunity to filter the pilot sufficiently early to prevent the severe rate limiting and to prevent an oscillatory departure for larger tasks. For this reason, 45 deg was chosen as a threshold for PA when simulating an unstable bare airframe configuration.

The final condition in a severe PIO is the frequency of the pitch rate oscillation ( $qF$ ). According to Mitchell, historical data reveals all severe PIO events have occurred in the one to eight rad/sec frequency range (Mitchell, 1994). Since the period of  $q$  was already calculated in the PA section, the frequency condition simply requires the conversion of the period of  $q$  into rad/sec:

$$qF = \frac{2\pi}{T} \quad (6)$$

The two switches have thresholds corresponding to one and eight rad/sec, respectively. The AND logic operator (bottom right of Figure 3-5) only passes a one value if both of the previous switch thresholds were satisfied (i.e. the signal frequency was greater than one AND less than eight rad/sec).

Min\_Max Logic Subsystem. The bottom level subsystem in this ROVER logic system is the Min\_Max Subsystem (see Figures 3-6 and 3-7). This subsystem receives the unfiltered  $q$  and  $\delta_{eCMD}$  and forwards the seven parameters discussed above in the ROVER Conditions Subsystem. In order to accurately determine parameters like  $q_{max}$

and  $t_{q\_min}$ , it is important to ensure noise does not drive the activation of local maximum or minimum values. This necessitates heavy filtering of both the  $q$  and  $\delta_{eCMD}$  signals via a fourth order Butterworth low-pass filter. The bandwidth of this chosen filter is 20 rad/sec, so it passes a nearly unattenuated signal in the frequency range of one to eight rad/sec. This filter severely attenuates all high frequency content of the signals, but at the expense of some phase distortion. However, since the same low-pass filter filters both signals, the phase distortion is identical for both signals. Furthermore, when the signal parameters are differenced in the ROVER Conditions Subsystem, the phase distortion is eliminated. This does introduce a slight time delay (on the order of 0.5 sec) in PIO detection because each relative peak for each signal is essentially shifted to the right. This was considered throughout the simulation and was found to have no adverse affect on either the timeliness or accuracy of the switching logic during ground simulation. This filtering delay will be investigated further in the flight test sections.

The remaining blocks in the Simulink® Min\_Max Subsystem act as slope detectors by referencing the current data point as well as the previous two points. From this, the current slope, along with the previous slope, can be determined. This subsystem determines and stores a local maximum whenever the previous slope was positive and the current slope is either zero or negative. The zero slope occurs quite frequently on the  $\delta_{eCMD}$  signal when position saturations are met. This logic identifies the first point, or leading edge, of a signal plateau as the maximum. Similarly, a local minimum is determined by a negative slope followed by a zero or positive slope. Once the local min or max is determined, that value is retained until such a time that the next peak or valley in that signal is reached. Since these values are retained, the Conditions Subsystem

always has access to real number values from which to make its own calculations. Time values associated with each minimum and maximum are retained in a similar manner. In the two figures that follow, the first shows the pitch rate logic (Figure 3-6), and the second displays the block diagrams for the elevator command logic (Figure 3-7). The additional switching blocks in Figure 3-7 simply enforce the position saturation values when the elevator is close to the deflection limits.

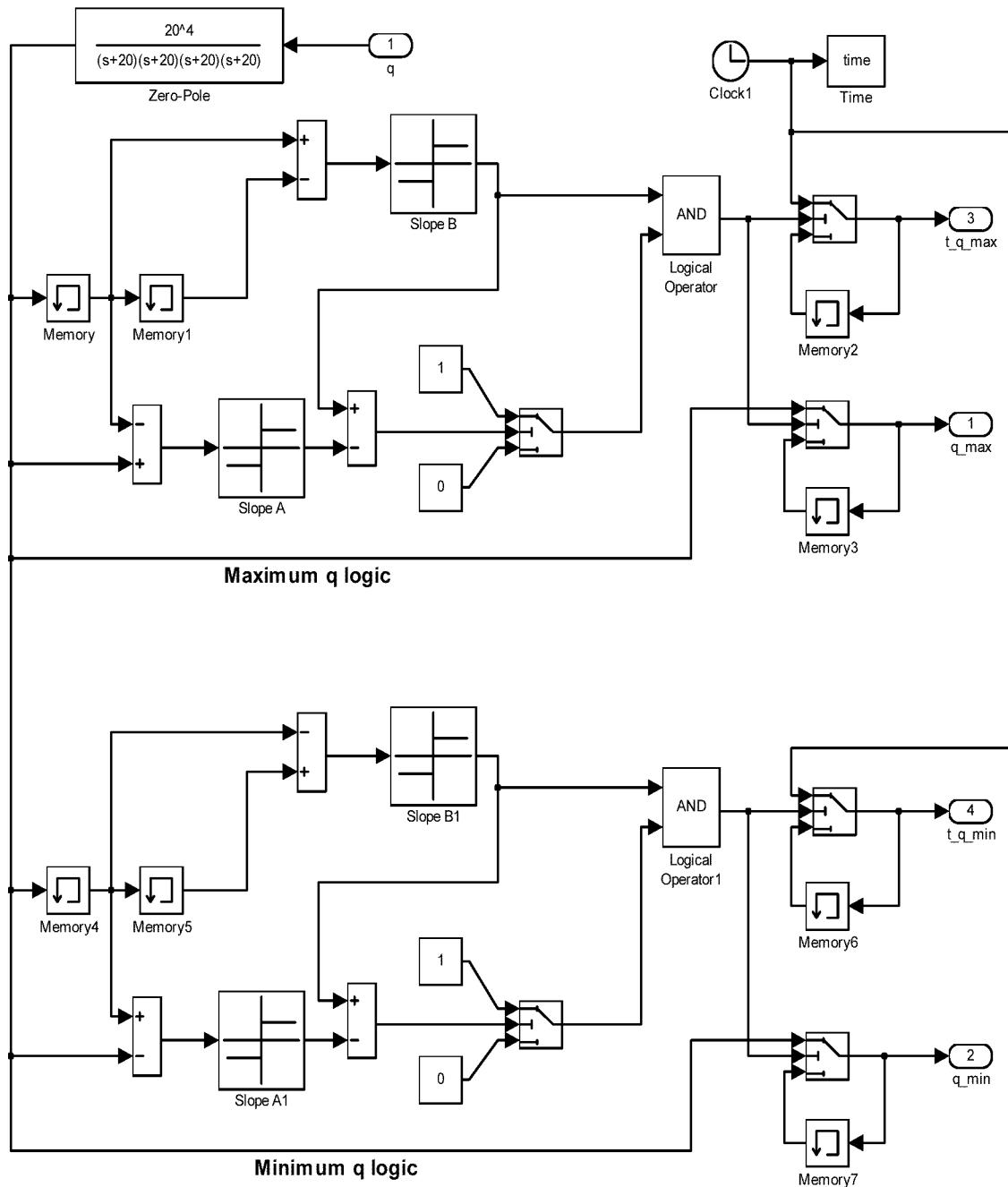


Figure 3-6. Pitch Rate Min\_Max Logic Subsystem

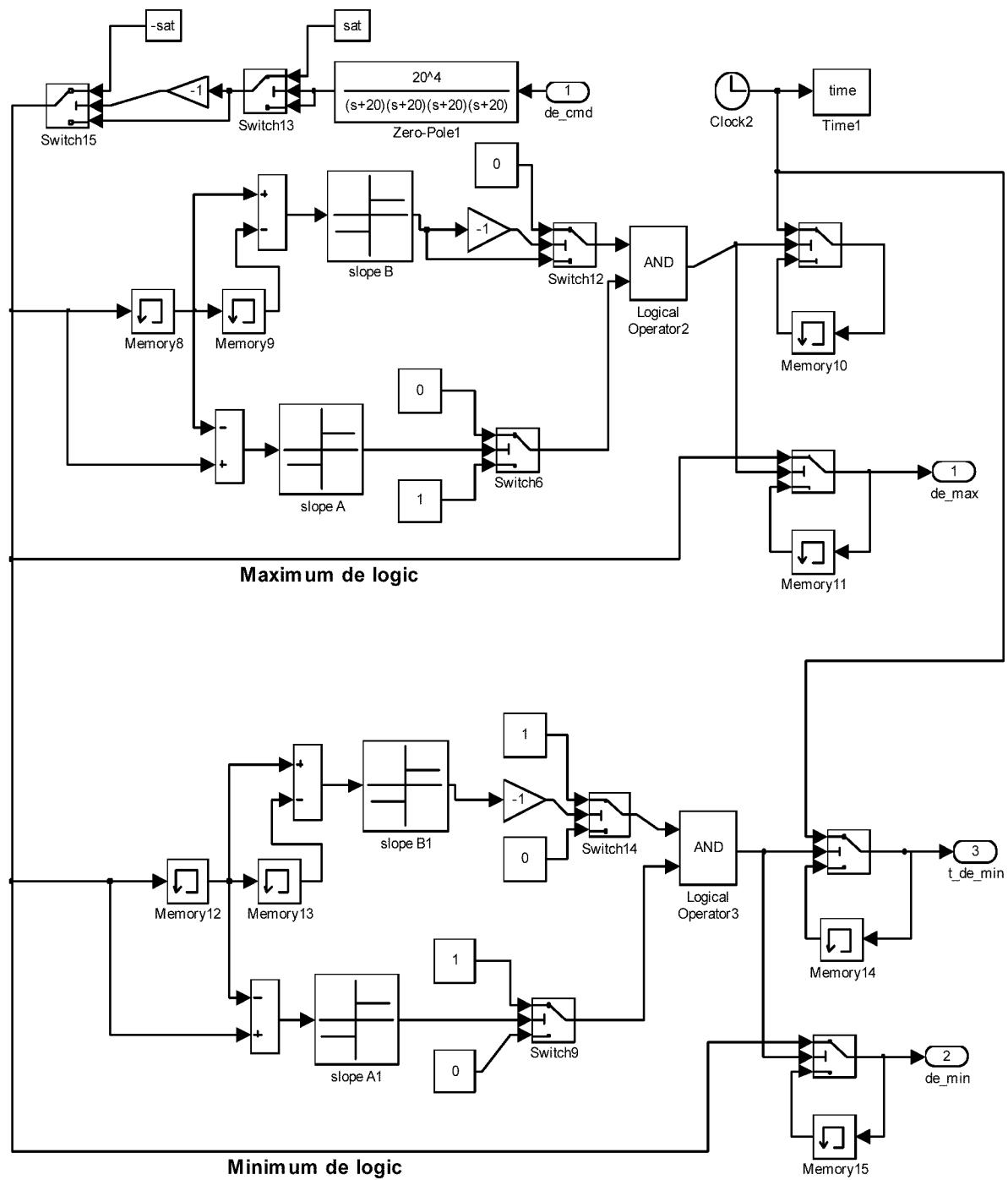


Figure 3-7. Elevator Deflection Min\_Max Logic Subsystem

This Min\_Max Subsystem was designed to eliminate the devastating effects that noise can have on this type of switching logic. Since the system acts as a slope detector, a noisy signal prevents the determination of any useful data. Figure 3-8 shows how band-limited white noise was injected into every simulation trial to mimic real world signal noise levels. The pilot command,  $\delta_{eCMD}$ , saw noise amplitudes up to 0.5 deg while the pitch rate signal was altered to include noise magnitudes up to 1.0 deg/sec. The fourth order Butterworth filter was adequate to suppress this injected noise and to allow for proper ROVER operation (see the top left block of Figure 3-6).

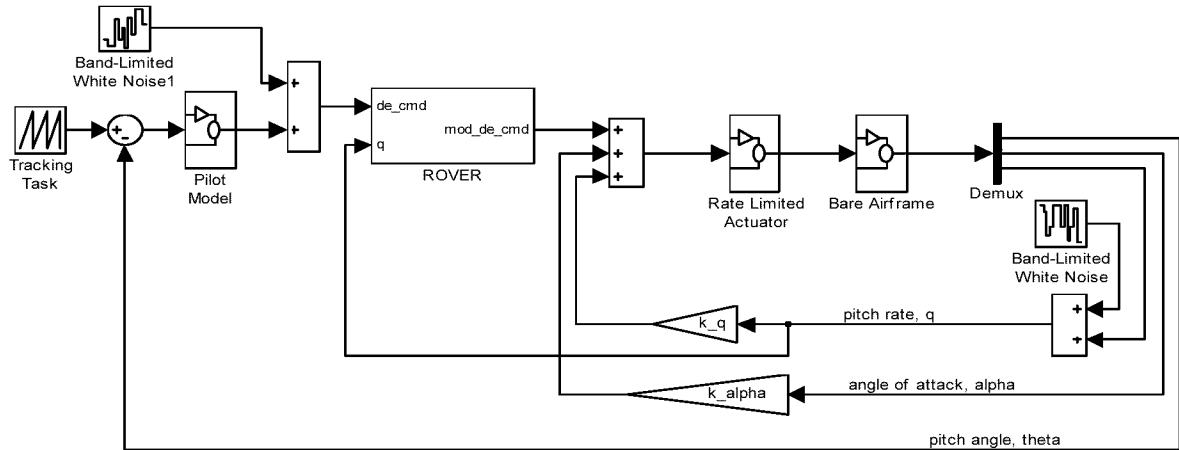


Figure 3-8. White Noise Injection into System Model

## Additional Simulation Configurations

As discussed in the previous section, the majority of initial simulations were run using a 60 deg/sec rate limit and a 35 deg elevator deflection saturation. However, under these conditions, Cases A and B would not develop into a severe PIO. In order to make these configurations more prone to PIO, a transport delay/equivalent time delay block was added to the top level Simulink® diagram just after the actuator (see Figure 3-9).

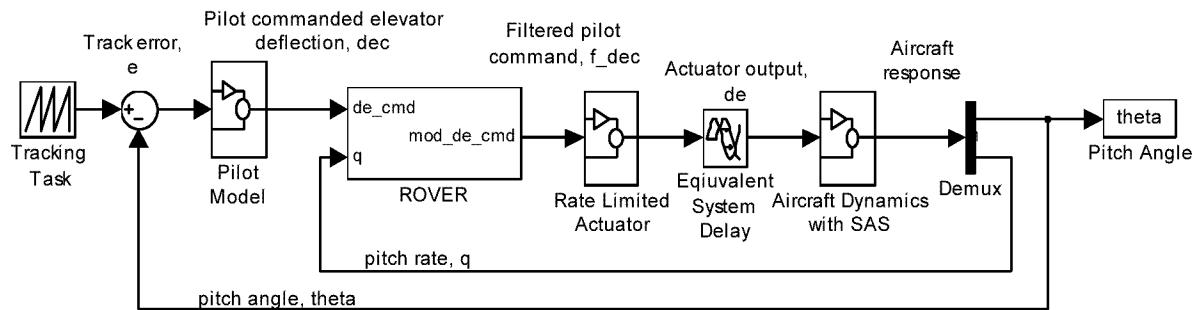


Figure 3-9. Increased Equivalent System Delay

The actual value of the time delay was not deemed as important as the resulting aircraft and ROVER response. Iterations on delay time ranged from 100 to 500 msec. The focus was on simulation performance and the ability of the ROVER system to detect and eliminate the PIO rather than the realistic nature of the time delay values. In Figure 3-10, Case A configuration is shown without any added delay (top) and with a 200 msec delay added (bottom). Figure 3-11 shows the same configuration now without and with ROVER. The ROVER on plot (bottom of Figure 3-11) resembles the Case A response before any delay was added (top of Figure 3-10).

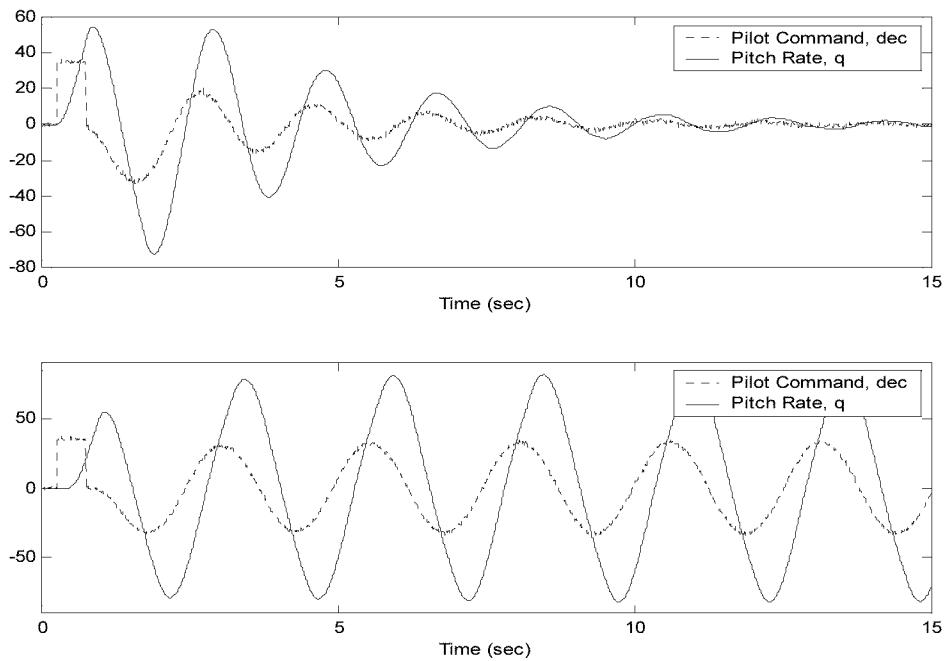


Figure 3-10. Case A Response with Excess Time Delay without ROVER  
(Top plot 0 msec, bottom plot 200 msec)

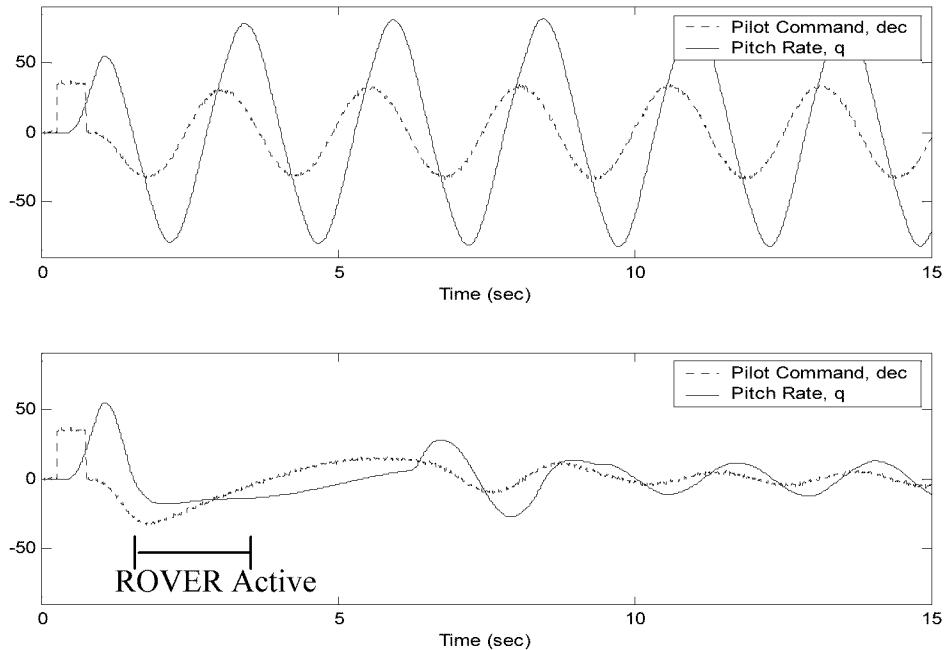


Figure 3-11. Case A Response with 200 msec Delay with and without ROVER  
(Top plot without ROVER, bottom plot with ROVER)

The lower plot of Figure 3-11 shows the dramatic effect of having a suppression filter in the command loop. Even with this significant delay added, the ROVER notch filter was only active from 1.2 to 3.0 seconds during the simulation. The response after ROVER turned off is still oscillatory but not large enough to be considered a severe PIO.

In each of the next four graphs (Figures 3-12 to 3-15), the top portion shows aircraft response without filtering. The bottom plot shows the improved performance with the PIO suppression filter.

Figure 3-12 demonstrates a very different phenomena than Figure 3-11. A 500 msec delay is now introduced immediately following the actuator dynamics. During this trial, the unfiltered response quickly developed into a severe PIO as evidenced by the sawtooth plot of pilot command. During this simulation, ROVER first detects the severe PIO at 1.5 sec. The PIO is temporarily suppressed, but again develops near the 7-second point. Again, the ROVER filter suppresses pilot commands up to about the 10 second point where the cycle repeats ... even though the tracking task has returned to zero. For clarity, the ROVER value is also presented on the bottom graph of Figure 3-12. The interesting point is that the ROVER filter does switch on and off automatically, but it cannot completely eliminate the continuance of undesirable aircraft motion. In this case, the equivalent time delay is so destructive that even the most stable bare airframe, a level 1 open loop configuration, can be driven into PIO. The ROVER algorithm, though, is still helpful in limiting the magnitude of the oscillation.

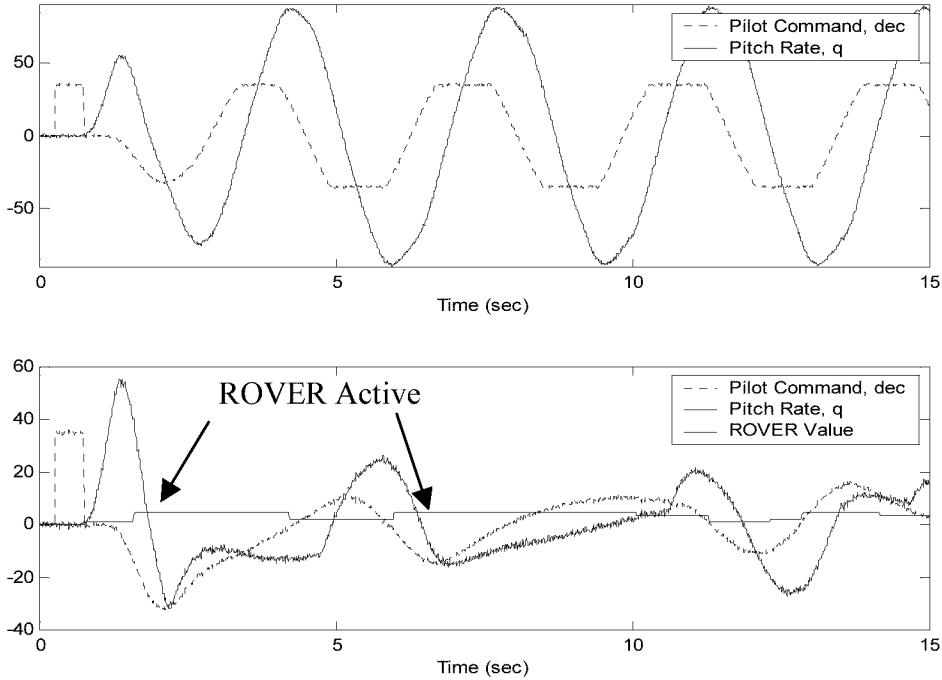


Figure 3-12. Case A Response with 500 msec Delay with and without ROVER  
(Top plot without ROVER, bottom plot with ROVER)

A different approach was taken to force Case B into a PIO. Instead of using the 60 deg/sec rate limiter, the modeled actuators were changed to a less capable system. Various rate limits, from 60 to 10 deg/sec, were explored. A 40-deg/sec limit proved to be another valuable data point for the ROVER evaluation. Figure 3-13 shows Case B's response to a 35 deg step input with rate limiting reduced to 40 deg/sec. Even though the traditional sawtooth pattern is not seen, the system is experiencing a fully developed oscillatory cycle, or severe PIO. The bottom plot shows the ROVER value along with  $q$  and  $\delta_{eCMD}$ . The ROVER filter activates at 1.2 sec and stays on for only one second. The bottom response is obviously more desirable than the response without a suppression filter.

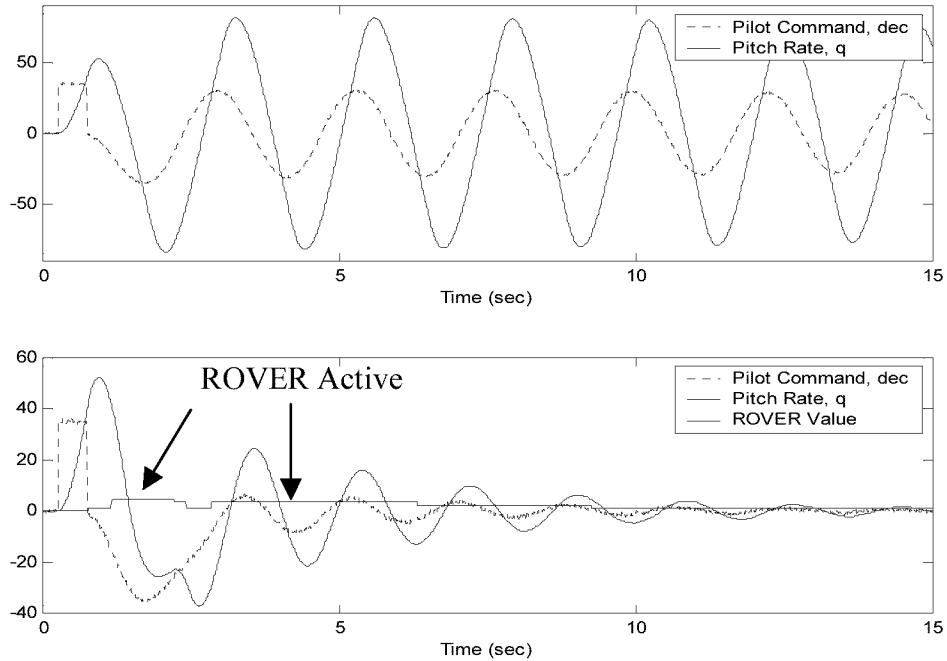


Figure 3-13. Case B Response with 40 deg/sec Rate Limiting  
(Top plot without ROVER, bottom plot with ROVER)

Due to its nearly unstable open loop poles, Case C will PIO. It displays the characteristic sawtooth  $\delta_{eCMD}$  plot (see Figure 3-14). The notch filter in this simulation has a dramatic effect. At 1.2 sec, a severe PIO has been detected and the pilot's command is attenuated for a total of 1.2 sec. The scale of both plots is identical to highlight the improved aircraft response.

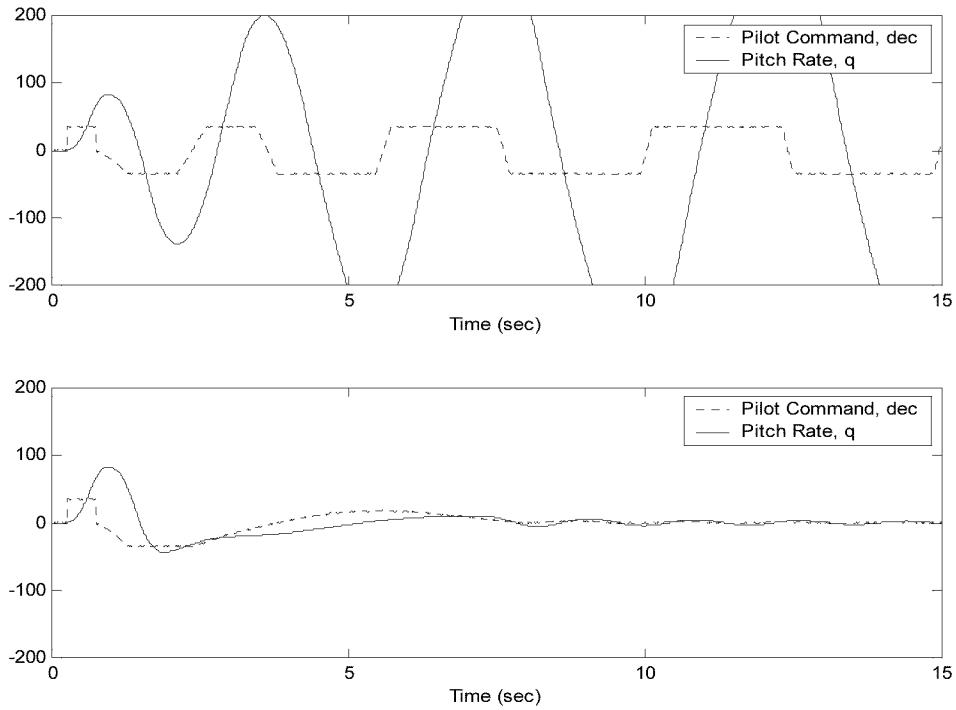


Figure 3-14. Case C Response to 35 deg Step and 60 deg/sec Rate Limiting  
(Top plot without ROVER, bottom plot with ROVER)

As discussed earlier, Case D has an unstable bare airframe and has a tendency to exhibit oscillatory departures. Figure 3-15 highlights this undesirable response to a 25 deg step input tracking task with rate and position limits set at the standard values of 60 deg/sec and 35 deg, respectively. Without a suppression filter, this aircraft departs controlled flight at about five seconds into the simulation. From seven seconds on, the pilot is applying full nose down stick command, but the aircraft is unresponsive. Once again, though, the ROVER filter made a timely determination that a severe PIO had developed and then filtered the pilot to avoid the oscillatory departure (see the bottom graph of Figure 3-15). During this trial, the filter only needed to actively attenuate the pilot command for a total of 1.5 sec, from 1.2-2.7 sec. After that time, the aircraft displays a lightly damped response as per its closed loop dynamics.

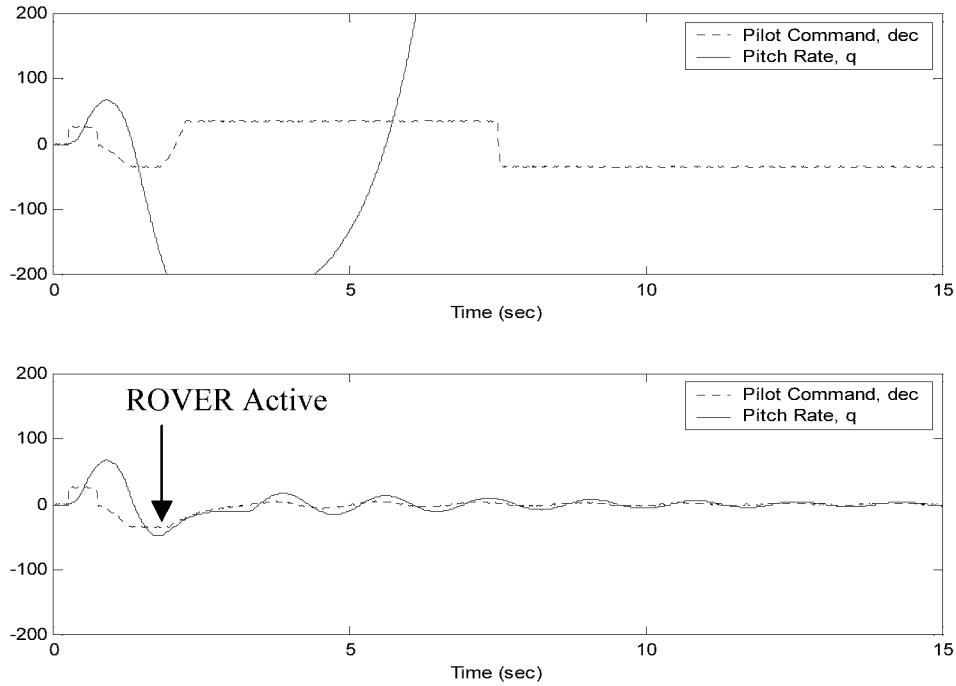


Figure 3-15. Case D Response to a 25 deg Step Input  
(Top plot without ROVER, bottom plot with ROVER)

It is essential to provide some control authority to the pilot even when the ROVER notch filter is attenuating the elevator command signal. In other words, the pilot must retain the capability to maneuver in the pitch axis. Because of this requirement, this notch filter was designed to provide low frequency authority to the pilot even when the ROVER filter was actively attenuating longitudinal commands. The next figure, Figure 3-16, shows each of the four case configurations attempting to track a low frequency ramp input in the presence of active filtering. This plot shows the ramp, a theta tracking task, as a dotted line and aircraft pitch angle,  $\theta$ , response as a solid line.

In order to validate this low frequency authority, the ROVER filter was commanded to remain on throughout the 15-second simulation. Each configuration displayed a slightly oscillatory response but had no difficulty tracking the ramp signal. This task resembles a low altitude PIO event in which the pilot decides to climb away from the ground. Even though ROVER has detected a severe PIO and is attenuating pilot commands in the oscillatory frequency range, the pilot retains authority to maneuver away from a potentially life-threatening situation.

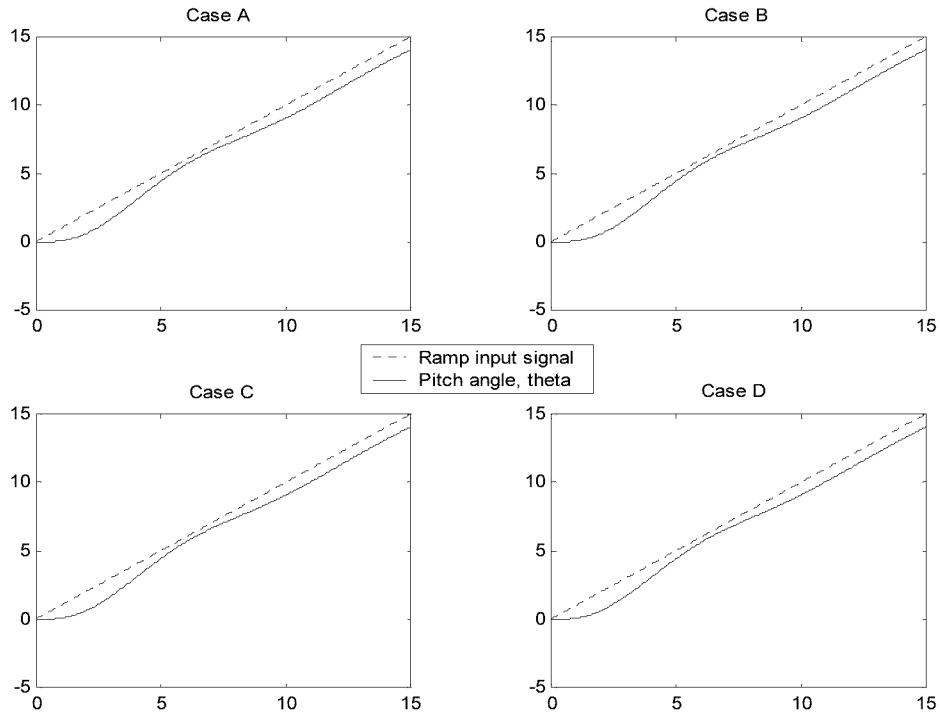


Figure 3-16. Aircraft Response to Ramp Input  
(Low Frequency Tracking Task)

## IV. Flight Test Preparation

Ground simulation results from the Simulink® computer model (see Figure 3-1) provided the foundation for the flight test configurations. In order to conduct the flight test project, the following items were organized and completed by the HAVE ROVER Test Team prior to the first evaluation flight: a test concept meeting, a test plan working group meeting, and a formal test plan including approval by a technical and safety review board. Because of the limitations imposed by the project budget, the test team was required to limit the test matrix and to emphasize priority test variables. The test team decided to evaluate bare airframe dynamics, rate limits, time delays, and tracking tasks as the primary variables, thus making the control stick dynamics and ROVER thresholds constant.

### Pre-Flight Organization

The HAVE ROVER Test Team consisted of three student test pilots, two student flight test engineers, and one student flight test navigator. The team was assigned a TPS staff test pilot to serve as an evaluation pilot and staff monitor. The following table shows the experience level of the four pilots who flew sorties for Project HAVE ROVER. Note all four test pilots have operational fighter experience.

Table 4-1. HAVE ROVER Team Test Pilots

Pilot Designation	Operational Aircraft Experience	Total Flight Hours
Pilot 1	Tornado	2300
Pilot 2	Tornado	1400
Pilot 3	F-16	1800
Pilot 4	F-15, F-16	1700

In accordance with the test plan, the responsible test organization (RTO) for this project was the 412<sup>th</sup> Test Wing, Edwards AFB (Johnson, Test Plan, 2001:1). The USAF TPS HAVE ROVER Test Team accomplished all testing and data reduction and analysis. The TPS staff drafted a technical adequacy letter following a technical review board (TRB). A three-member safety review board (SRB) determined the project had a low level of risk. Veridian Engineering, Flight Research Group was contracted to configure the variable stability system (VSS) and to operate and maintain the Variable Stability In-flight Simulator Test Aircraft (VISTA) evaluation aircraft. Mr. Andy Markofski served as the focal point at Veridian for all simulation questions and implementation issues while Mr. Jeff Peer served as the safety pilot and addressed safety of flight concerns.

## **Flight Test Overview**

The HAVE ROVER Test Team had one over-arching goal for project: to evaluate the ability of a Real-time Oscillation VERifier (ROVER) switching algorithm to detect and suppress pilot-induced oscillations (PIOs) in the longitudinal axis. The project was limited in scope by considering only the longitudinal axis and by the combination of aircraft configurations flown.

The test team determined that each configuration flown would require approximately seven minutes of flight time to thoroughly evaluate. The determination of this time is detailed in the Tracking Task section below. Since the HAVE ROVER Project was authorized 12 sorties equating to approximately 13 hours of evaluation time, the team generated the following configuration table with four priority levels to be used as the test matrix (see Table 4-2). It was estimated that all priority one test points could

be completed by the sixth evaluation sortie and could therefore be completed prior to flying against an airborne target.

The Code in the far left column of Table 4-2 was used during flight between the safety pilot (SP), evaluation pilot (EP), and telemetry (TM) room to establish the desired configuration without the evaluation pilot knowing the exact elements of the configuration. The VSS code was generated by Mr. Andy Markofski at Veridian as a means for the safety pilot to enter the configuration into the VSS via the upfront control entry panel. The trailing X was an integer for the remaining fuel in thousands of pounds.

The priority numbers ranged from one (highest and most critical for flight test analysis) to four (lowest but still desired to populate data plots). Case A through D refers to the same bare airframe dynamics detailed in Chapter 2. The rate limit was imposed inside the VSS computer simulation prior to sending the command signal to the aircraft actuators. The limits chosen were steps of 15 deg/sec from 60 deg/sec down to 15 deg/sec. The time delay (in milliseconds) was an additional system time delay injected into the simulation in the forward loop (see Figure 3-9). This variable was deemed the lowest priority as current aircraft and flight control systems rarely display time delays over 100-150 msec.

Table 4-2. HAVE ROVER Configuration Decoder Table

Code	VSS	Priority	Case	Rate Limit	Time Delay
Q	60X	2	A	60	0
W	61X	2	A	60	100
E	62X	1	A	60	200
R	63X	4	A	60	300
T	70X	2	B	60	0
Y	71X	2	B	60	100
U	72X	2	B	45	0
I	73X	2	B	45	100
O	74X	1	B	45	200
P	75X	4	B	30	0
A	76X	4	B	30	100
S	77X	4	B	30	300
D	80X	1	C	60	0
F	81X	3	C	60	100
G	82X	3	C	60	200
H	83X	1	C	45	0
J	84X	1	C	45	100
K	85X	3	C	45	200
L	86X	1	C	30	0
Z	87X	1	C	30	100
X	88X	3	C	30	200
C	89X	1	C	15	0
V	91X	1	D	15	0
B	93X	1	D	30	0
N	94X	1	D	45	0
M	96X	1	D	60	0

### Test Article Description

The four Simulink® aircraft models mirror the work done by Captain Mike Chapa in the HAVE FILTER TPS Project and were discussed in Chapter 2 (see Table 2-1). Each consecutive bare airframe (from case A to D) exhibited decreasing stability. However, the stability augmentation system feedback was designed to provide identical closed loop dynamics for all four configurations. The parameters for these bare airframe dynamics were given to Veridian to match for the flight test portion of the project. No

specific guidance was given concerning lateral-directional handling qualities, so Mr. Markofski implemented the lateral-directional dynamics from a previous project that displayed good handling qualities (Markofski, 1999).

VISTA stick dynamics for this evaluation displayed level 1 characteristics and were not a variable during this evaluation. The stick characteristics were chosen by Veridian engineers in order to provide good handling characteristics (Markofski, 1999). These stick parameters were modeled after the F-22 sidestick (Johnson, Test Plan, 2001:46). In previous tests, these stick dynamics had shown good performance for operationally representative tracking tasks performed in VISTA. Originally, the author had desired to compare sidestick performance with centerstick trials, but this was later determined to be a low priority. Only sidestick test points were flown in this evaluation in order to reduce the size of the test matrix.

As per the request of the HAVE ROVER Test Team, Veridian implemented a mechanism to adjust ROVER thresholds in flight. The team wanted to have access to change these critical values if early evaluation sorties proved to perform significantly different from the ground simulations. The team decided to fix the thresholds no later than the third evaluation sortie in order to have sufficient data for comparison. The modeling and simulation thresholds, and therefore the beginning threshold values for the flight test portion, were:

- 1) PR > 12 deg/sec,
- 2) ED > 5 deg,
- 3) PA > 65 deg, and
- 4)  $1 < qF < 8$  rad/sec.

Because it required an additional setup input during flight, 65 deg was used as the phase angle (PA) threshold for all airframe configurations. This was contrary to earlier ground simulation results but resulted in more efficient data collection.

### **Flight Test Aircraft Description**

The NF-16D VISTA was a modified F-16D Block 30, Peace Marble II (Israeli version) aircraft with a digital flight control system using Block 40 avionics (USAF S/N 86-0048). A Pratt & Whitney F100-PW-229 engine powered the aircraft. To allow the pilot in command, the SP, to fly from the rear cockpit, all necessary controls were moved from the front to the rear cockpit. The rear cockpit had conventional F-16 controls except that the throttle was driven by a servo, which followed electrical commands of the front cockpit when the VSS was engaged. Primary system engagement and VSS controls and displays were located in the rear cockpit. The front cockpit included the VSS control panel needed for the EP to engage the variable feel centerstick or sidestick, but only the SP could engage the VSS system.

Other modifications to the aircraft included a high flow rate hydraulic system with increased capacity pumps and higher rate actuators. The maximum actuator rate was approximately 69 deg/sec. In addition to the modified hydraulic system, VISTA had modifications to the electrical and avionics systems required to support VSS operations. Additionally, the VISTA VSS had several safety trips operating to ensure no airframe limits were exceeded. Many of the VSS trips were predictive in nature and would disengage the VSS if the aircraft was approaching a structural limit at a significant rate.

During all test sorties, the aircraft was configured with a centerline fuel tank to increase time on conditions during the evaluations. For every evaluation sortie, a HAVE ROVER Test Team pilot flew as the EP while Mr. Jeff Peer, a Veridian pilot, performed the SP duties in the rear cockpit.

### **Rating Scales**

The rating scales used by the HAVE ROVER Test Team were the TPS standard Cooper-Harper Rating (CHR) scale and a PIO Rating (PIOR) scale. The test team also developed a new scale for documenting nuisance activations of the ROVER filter, the Nuisance Rating (NR) scale. All three of these scales are presented in Appendix C.

### **Flight Test Objectives**

The overall test objective was to evaluate the ability of the ROVER switching algorithm to detect and suppress pilot-induced oscillations in the longitudinal axis of a digital flight control system. The specific flight test objectives were:

- To verify that the dynamics, rate limits, and time delays of the four configuration simulations were properly implemented into VISTA's on-board computers.
- To evaluate the ability of the ROVER algorithm to accurately detect PIOs in the presence of rate limiting and/or system time delay.
- To evaluate the ability of the ROVER longitudinal notch filter to suppress PIOs during operationally representative Category A tracking tasks.
- To compare task performance with ROVER suppression algorithm engaged and disengaged.

Configuration Validation. For the first objective, the test team needed to verify the accuracy of simulation parameters implemented by Veridian. The measure of performance (MOP) associated with this objective was the simulation response to various input signals. The desired response format included both time histories and frequency analysis Bode plots. A minimum of one Bode plot and time history of aircraft response to a step input was required for each of the four configurations for both open and closed loop. Additionally, the six test points listed below were created to validate the time delays and rate limits.

Table 4-3. Test Matrix for Validation (MOP 1)

Rate limit (deg/sec)	A	B	C	D
60	0,300	0	0	0
45			0,100,200	
30			0	
15			0	

Note: 1) The numbers in the table specify the configuration time delays (in milliseconds).

The test team established the following criteria as a “goodness” measure of the VSS computer models. Any parameters determined to be within these criteria values were considered adequate for this project. In order to determine these values, pilots used manual and/or programmed test inputs (PTIs) to gather the necessary data during the calibration and validation flights. Test inputs included step inputs and frequency sweeps to determine both open and closed loop dynamics.

Table 4-4. Evaluation Criteria for Configuration Verification

Parameter tested	Evaluation criteria
Time response - dynamics	Qualitative evaluation / engineering judgment
Frequency response- dynamics	Qualitative evaluation / engineering judgment
Time delay	Within 25 msec of the planned time delay
Rate limit	Within 3 deg/sec of the planned rate limit

PIO Detection. PIO detection was the second objective and was the heart of this project. Without proper detection and a low nuisance rate, pilots would never accept such a filter in an operational aircraft. In order to evaluate the ROVER detection rate, the test team used PIO ratings (PIORs) and ROVER integer values (RIVs) from Phase 2 and Phase 3 tasks as the measures of performance, MOP 2. Phase 2 and 3 maneuvers are detailed in the Tracking Task section below. These parameters were recorded only while the ROVER suppression logic was disengaged. By monitoring the RIV without allowing the filter to suppress pilot commands, the test team was able to build a database of pilot comments and ratings about each aircraft configurations prior to ROVER suppression.

The team decided to require a minimum of two pilots to complete each of the priority one test points specified in table above (see Table 4-2). Completion of each configuration required the pilot to perform and comment on both the HUD tracking task and the airborne target tracking task. The evaluation criterion is shown below (see Table 4-5). A correct detection was when either: 1) the pilot identified a PIO, assigned a PIOR of four or higher, **and** ROVER also classified the oscillation as a severe PIO with a RIV of four, or 2) the pilot did not experience a PIO, assigned a PIOR of 3 or lower, **and** ROVER determined a RIV of less than four. Either of the above situations resulted in a satisfactory evaluation point and a correct detection. It was unsatisfactory if the pilot reported a PIO and ROVER did not, or when the pilot did not report a PIO and ROVER did. In order to report success, the test team required correct detections over 80% of the time with a nuisance rate/false alarm rate of less than 10%.

Table 4-5. ROVER Detection Evaluation Criteria

ROVER Calculation	Assigned PIO Rating	Evaluation
PIO Detected (RIV=4)	PIOR $\geq 4$ (or VSS Safety Trip Engaged)	Satisfactory / Correct Detection
	PIOR $\leq 3$	Unsatisfactory / False Detection
PIO Not Detected (RIV<4)	PIOR $\geq 4$ (or VSS Safety Trip Engaged)	Unsatisfactory / Non-Detection
	PIOR $\leq 3$	Satisfactory / Correct Detection

PIO Suppression. The third objective was to evaluate the algorithm's ability to suppress PIOs. MOP 3 was identical to MOP 2 with the exception that ROVER was allowed to activate automatically during these trials. With the database of aircraft performance compiled during objective 2, this objective allowed the test team to quantify ROVER's ability to suppress undesirable PIO motions. The team again attempted to collect at least two sets of pilot assigned PIORs and corresponding RIVs with ROVER suppression engaged for each of the priority one test point. The further stipulation here was that only those points which resulted in a PIOR of four or higher **and** a RIV of four during objective 2 tasks were of interest. While detection is concerned with nuisance activations and false detections, suppression is not. Suppression was dependent upon a RIV of four (a ROVER activation) and was therefore required for this objective.

The evaluation criterion for this objective was a reduction in PIO rating for 80% of the test points. In addition, a ROVER activation which eliminated a previously observed VSS safety trip was also considered a satisfactory result.

Pilot Performance with ROVER. Objective 4 looked specifically at task performance with ROVER engaged versus disengaged. The associated MOPs for this objective were tracking error percentages, CHRs, and nuisance ratings (NRs) for Phase 3

tasks. The test team again collected a minimum of two sets of tracking error percentages, CHRs, and corresponding NRs with ROVER suppression engaged and disengaged, for each of the priority one test point which resulted in a PIOR of four or higher during objective 2 tasks. The evaluation criterion was that the mean of all tracking error percentages increased with at least 80% confidence. Additionally, the team determined that the CHRs should decrease in 80% of the test points, the ROVER activations should not be a Type 1 nuisance to the pilot more than 10% of the time, and Type 3 nuisance ratings were allowed not more than 20% of the time (see Figure C-3).

During the airborne target tracking task, the pilot locked the aircraft radar on the target aircraft. The angular error between the center of the 10-mil fixed reticle and the radar line-of-sight was used to calculate the tracking error (see Figure 4-1). The tracking error percentage was the percentage of overall data points that were found to lie within 10 and 20 mils for desired and adequate performance, respectively.

## **VISTA Ground Simulation and Target Aircraft**

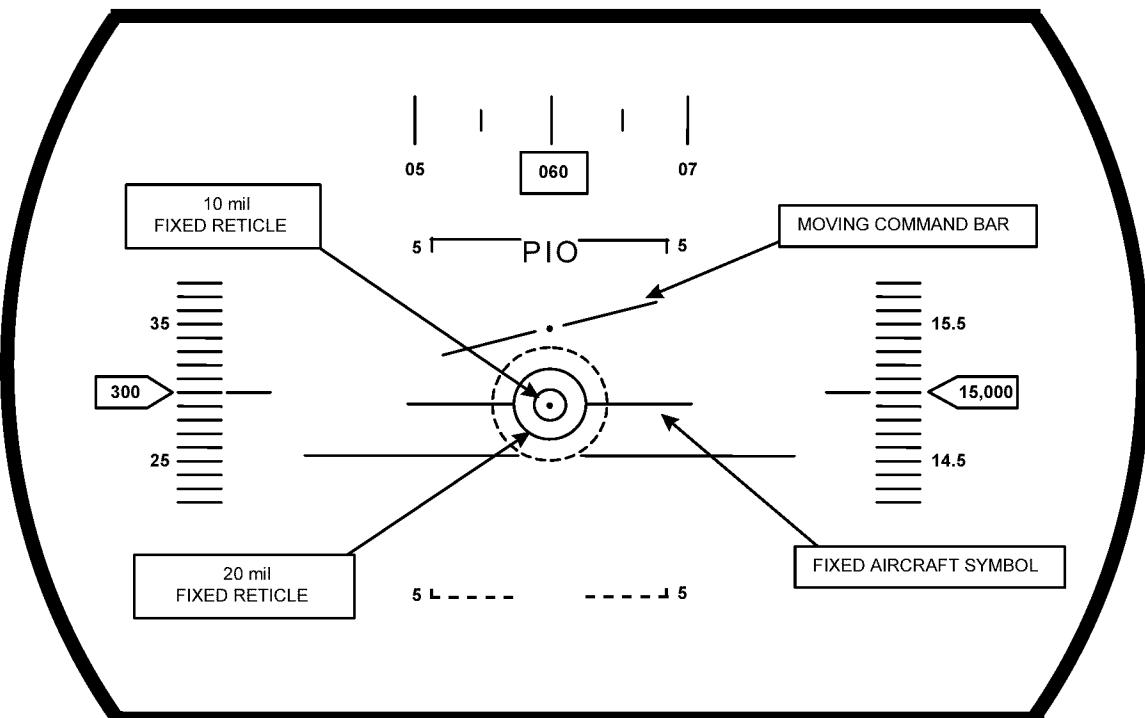
Before flight testing commenced, the VISTA NF-16D aircraft was used in the power-on ground mode with the variable stability system (VSS) engaged. Each team member had the opportunity to exercise the heads-up display (HUD) tracking task and the ROVER switching logic for several aircraft test configurations. The purpose of this simulator session was to familiarize each test team member with the VISTA symbology, ROVER symbology, and the HUD generated tracking task (discussed in the next section). Since only the test pilots were able to fly the evaluation sorties, this experience for the remainder of the test team proved important during post-flight debriefs and data analysis.

The support aircraft desired by the HAVE ROVER Test Team was the T-38 Talon. Because of its performance, availability, and relatively low per hour cost, the T-38 was the ideal choice for target aircraft. This target was flown as an airborne gunnery target on six of the test sorties to evaluate the operational suitability of the ROVER algorithm and notch filter. These sorties were flown after the majority of the HUD tracking task test points had been completed and the team had a good idea as to the results of ROVER during air-to-air tracking.

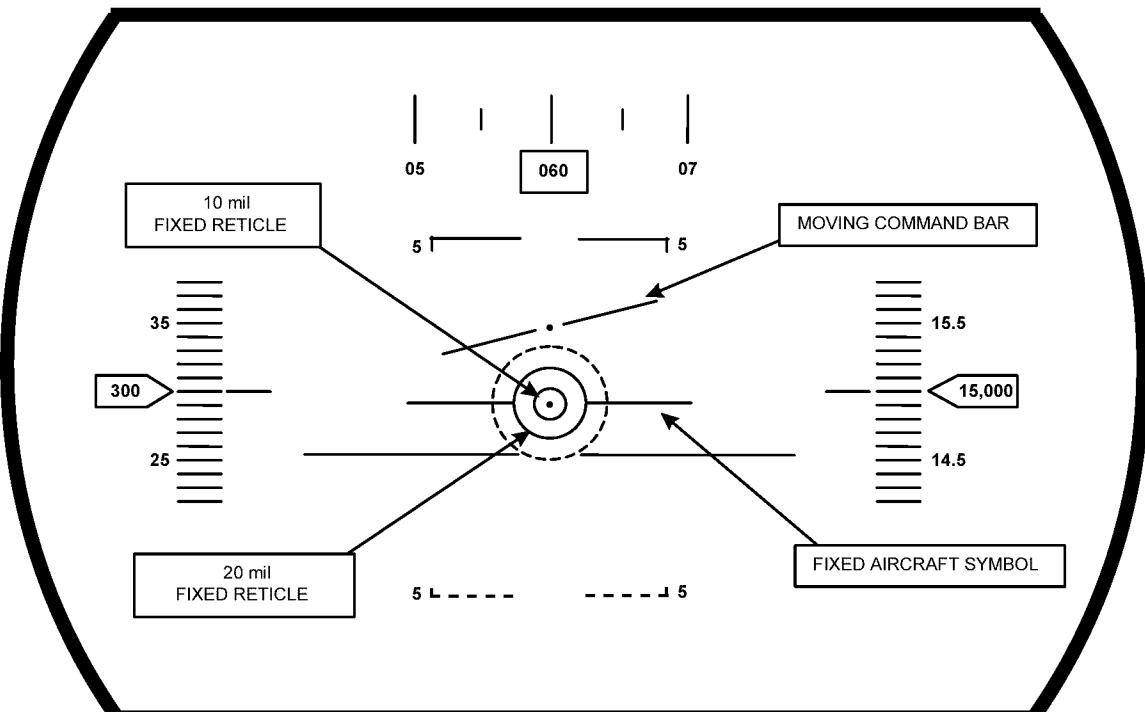
Because of the T-38's limited turning performance at 300 KIAS, the test team decided to explore pushing the VISTA evaluation aircraft to a slightly faster airspeed while allowing the T-38 to fly sustained turns between 330 and 350 KIAS. Mr. Markofski agreed that 320 KIAS would still be close enough to the design point of the VISTA simulated configurations to allow for valid data collection and comparison.

## **Tracking Tasks**

The HUD generated tracking task chosen for this project was the 140-second MIL-HDBK 1797 task shown below (see Figure 4-2). The team decided to terminate the task at 75 seconds in order to increase the number of configurations flown. Both the roll and pitch tasks were incorporated together by Veridian and displayed in VISTA. The moving command bar in Figure 4-1 moved in the HUD to show the evaluation pilot where to aim the fixed reticle pipper. The pilot's task was to align the dots and hold the moving command bar dot inside the inner ring (10-mil ring) of the fixed pipper. Figure 4-1 also shows the "PIO" display shown to the pilot when the ROVER notch filter engaged due to a RIV of four.



**ROVER Filter Engaged**



**ROVER Filter Disengaged**

Figure 4-1. HUD Tracking Task Symbology

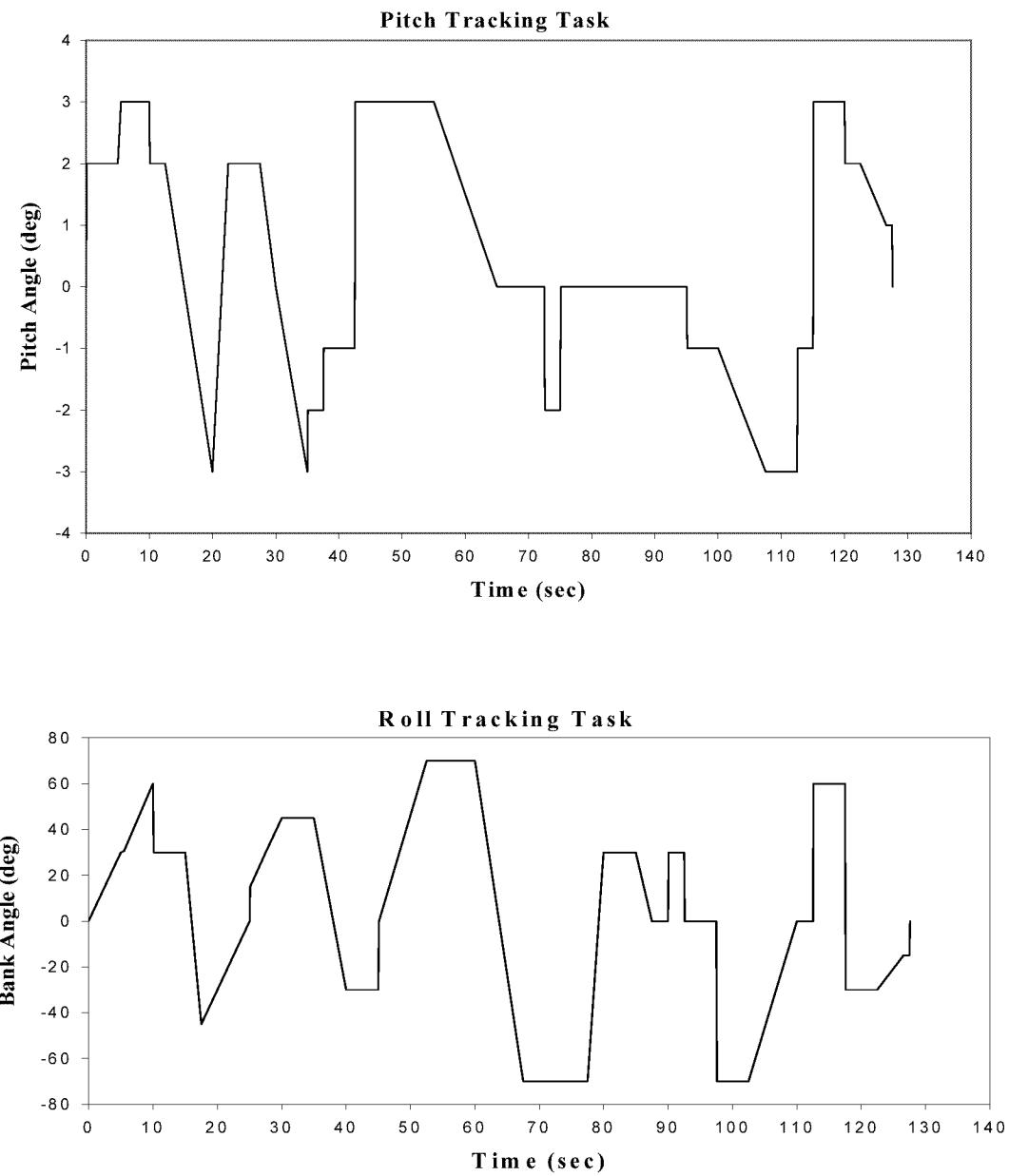


Figure 4-2. HUD Tracking Task

The evaluation pilot conducted Phase 1, 2, and 3 handling qualities evaluations for each test point in accordance with the guidance below.

*Phase 1:* Perform gentle pitch captures and semi-closed loop tracking, progressing from small to large amplitude. The EP attempted to track the HUD generated target within the HUD field of view. This familiarized the EP with the feel of the aircraft and provided insight into future task performance.

*Phase 2:* Perform the HUD tracking task shown in Figure 4-2 using aggressive and assiduous tracking striving for zero track error. During or immediately following the task, record pilot comments and assign a PIO rating using the scale shown in Figure C-2. In an attempt to minimize task predictability, the safety pilot placed a random gain of  $\pm 1$  in front of the roll task between various tasks and configurations.

*Phase 3:* Perform aggressive tracking to place the pipper over the target. At the beginning of the task, the evaluator pilot should immediately transition to aggressive tracking of the HUD target and attempt to place the 10-mil fixed reticle over the generated target/moving command bar using whatever pilot compensation technique desired (Figure 4-1). The task will continue until the EP experiences a PIO (PIOR of four or higher) or the 75-second task is completed (Figure 4-2).

The overall timing for each test point was determined to be approximately seven minutes. The Phase 1 and 2 maneuvering were estimated to run for one minute combined while the Phase 3 task was estimated to run for no longer than 75 seconds. Repeating this sequence and allowing for time to configure the aircraft from the rear cockpit, as well as affording time to transfer aircraft control and position the aircraft properly in the airspace, the test team concluded seven minutes per configuration would be adequate.

The airborne target tracking task developed for this project modeled gun employment during aerial combat. Prior to starting the task, the target aircraft stabilized at approximately 350 KIAS and 15,000 ft PA. At the beginning of the task, the target pulled three G's in a level turn into the fighter's (VISTA's) position. From a position approximately 30 degrees off and 2500-3000 feet behind the target aircraft, the EP aggressively pulled toward the target's 6 o'clock and then performed an unloaded reversal and pulled the pipper to the target aircraft (gross acquisition). In order to generate more angle off and larger pilot commands, the VISTA was flown to lag approximately every 90 deg of turn. This produced several additional opportunities to evaluate gross acquisition.

The pilot attempted to maneuver the aircraft to place the depressed reticle over the target aircraft's front canopy (fine tracking). The target abruptly varied the G loading from two to four G's at discrete time intervals during the level turn. The target called 180 and 360 degrees of heading change during the maneuver. While the maneuver was planned for 360 degrees of tracking, the EP called to terminate maneuvering when he had seen enough to make a valid assessment of the aircraft's performance. The desired and adequate criteria were:

**Desired:** Remain inside 10-mil diameter circle 50% of the time.

**Adequate:** Remain inside 20-mil diameter circle 50% of the time.

## **Telemetry and Data Collection**

All flight test sorties were flown at the Air Force Flight Test Center (AFFTC), Edwards AFB, CA. Mission telemetry (TM) was conducted at the USAF TPS building while the test aircraft operated in the R-2515 airspace. Standard USAF TPS frequencies were used for the TM room and UHF communications. A parameter list and instrumentation plan is attached in Appendix C. The primary and secondary TM frequencies were 1468.5 and 1476.5 MHz, respectively

All parameters of interest were recorded by the VISTA on-board systems and were downloaded after each test sortie. The TM room provided valuable real-time parameter and data review but played no safety role in the test. Therefore, an operable TM room was desired but was not a requirement for any of the evaluation sorties.

## **V. Flight Test**

All flight testing was conducted in Edward's restricted airspace R-2515 at an altitude of approximately 15,000 ft pressure altitude and 300 KCAS. The HAVE ROVER Test Team flew all of the validation and evaluation sorties between 05 and 17 October 2001. A T-38 aircraft was flown to support six of the evaluation sorties, numbers five to seven and nine to eleven. During the airborne target tracking tasks, the evaluation aircraft was flown at approximately 320 KIAS in order to more closely match the maneuvering speed of the T-38 target aircraft. The project required a total of 15.6 VISTA flight hours and 7.1 T-38 target hours.

### **Limitations**

The primary limitation encountered during the project was with the telemetry (TM) system at the TPS facility. Because the TM system lacked the range to allow the evaluation aircraft to travel more than 25 miles from the antenna, all sorties were flown in the congested airspace directly over Edwards AFB. Several runs experienced severe TM dropouts while several others required excessive maneuvering by the evaluation aircraft in order to maintain within the reception area. It was estimated that approximately one configuration per sortie was lost due to airspace limitations imposed by the limited TM capability.

Another limitation encountered by the HAVE ROVER Test Team was the requirement to fly two sorties per day, to double-turn the VISTA F-16. Due to scheduling and budget issues beyond the scope of this project, the HAVE ROVER Project attempted to complete all ground and flight testing within a 2-week window in

early October. This precluded the team from analyzing the data between sorties and potentially adjusting the ROVER thresholds to optimize performance. Once the thresholds were observed and validated (after the validation sortie), no changes were made to the condition thresholds.

### **Configuration Validation**

A Veridian flight crew flew two calibration sorties on 03 and 05 October 2001. Additionally, one validation sortie was flown by a HAVE ROVER pilot on 05 October. During the calibration and validation sorties, the flight crew performed several maneuvers to validate the dynamics in accordance with objective 1, configuration validation. Several pitch doublets and frequency sweeps were performed to determine both the open and closed loop dynamics. All test points in Table 4-3 were flown to verify the VISTA dynamics.

The test objective was met as all four of the aircraft configurations (A through D), all four rate limits (60 to 15 degrees per second), and all four time delays (0 to 300 milliseconds) were observed. Tables 5-1, 5-2, and 5-3 below highlight the critical parameters compared between flight test and ground simulation/Simulink® modeling. The Simulink® parameters were the desired parameters that Veridian was striving to duplicate. The largest difference was seen in the closed loop short period frequency. The difference between the desired and actual short period frequency was 7.3%. Based on this maximum difference and engineering judgment, all of the configurations listed below, both open and closed loop, were deemed satisfactory for this project.

Table 5-1. Flight Test versus Simulation Parameters – Configuration

Configuration	Short Period freq (rad/sec) from simulation	Short Period freq (rad/sec) from flight test	Short Period damping ratio from simulation	Short Period damping ratio from flight test
Open Loop A	3.13	3.15	0.70	0.68
Open Loop B	2.34	2.42	0.61	0.60
Open Loop C	0.86	0.86	0.99	0.99
Open Loop D	$T_{\text{double}} \approx 0.6 \text{ sec}$	$T_{\text{double}} \approx 0.5 \text{ sec}$	N/A	N/A
Closed Loop	3.13	2.90	0.70	0.69

System time delays and rate limits are summarized below in Tables 5-2 and 5-3.

These values were apparent from post-flight time history analyses (see Appendix B, Figures B-1 through B-6). Rate limits were determined from the slope of elevator deflection curve immediately following a step programmed test input (PTI). Time delays were determined from PTI step inputs by observing the delay between the commanded actuator rate and the actual change in elevator deflection due to that command.

Table 5-2. Flight Test versus Simulation Parameters – Rate Limits

Desired Rate Limits (deg/sec)	Flight Test Rate Limit (deg/sec)
60	60
45	43
30	31
15	15

Table 5-3. Flight Test versus Simulation Parameters – Time Delays

Desired Time Delays (msec)	Flight Test Time Delay (msec)
0	$\approx 0$
100	$\approx 85$
200	$\approx 160$
300	$\approx 300$

Evaluation criteria for configuration verification from the test plan are given in Table 5-4. By analyzing each configuration's response to a longitudinal frequency sweep, open and closed loop Bode plots were drawn. Figures B-7 through B-29 show each configuration's Bode plot for VISTA flight-tested response and for Simulink® ground simulation. Open loop configurations were flown in support of this objective; however, only closed loop configurations were flown during the evaluation sorties. All parameters and Bode diagrams were within the desired evaluation windows, or were close enough, using engineering judgment, in the case of the 200 msec delay, and were therefore considered satisfactory for this test program.

Table 5-4. Evaluation Criteria for Configuration Verification

Parameter tested	Evaluation criteria
Time response - dynamics	Qualitative evaluation / engineering judgment
Frequency response- dynamics	Qualitative evaluation / engineering judgment
Time delay	Within 25 msec of the planned time delay
Rate limit	Within 3 deg/sec of the planned rate limit

## PIO Detection

The second objective of this project focused on the ability of the ROVER algorithm to accurately detect PIO occurrences during Phase 2 and 3 maneuvering with ROVER's suppression logic disengaged. The evaluation pilots (EPs) conducted Phase 1, 2, and 3 handling qualities evaluations for each priority one test point. The specific piloting technique is detailed in Chapter 4. ROVER's PIO suppression logic was not engaged during the test points evaluated in this objective.

Table 5-5 shows ROVER's detection results as a function of the EP's observation. For this project, pilot comments and ratings were taken to be the truth source. A PIO

rating (PIOR) of less than or equal to 3 indicated that the pilot felt that no PIO had been encountered, while a PIO rating of 4 or greater signified that a PIO had occurred. These ratings were compared to the ROVER integer values (RIVs). Any task that resulted in a RIV value of four was considered to be a ROVER detection of a PIO. For example, if the pilot did not observe a PIO and therefore assigned a PIOR of 3 or less, an accurate ROVER detection would require a RIV of less than four (no severe PIO detected).

Overall, the ROVER algorithm correctly characterized pilot observations of aircraft motion 72% of the time. This value fell short of the desired goal of 80% set out in the evaluation criteria. Table 5-5 indicates that the majority of incorrect detections occurred when ROVER detected a PIO contrary to pilot observations (a false detection problem). When the pilots observed no PIO, ROVER replied in kind only 34% of the time. Such false detections could create a nuisance situation for the pilot if ROVER's suppression logic was engaged (see the next section). Conversely, when the pilots perceived a PIO, ROVER correctly identified it in 91% of the cases. This rate exceeded the desired detection level of 90% detailed in the evaluation criteria.

Table 5-5. Overall ROVER Detection Results

ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO	Overall Correct Detection Rate
18 of 53 (34%) <sup>*</sup>	96 of 105 (91%) <sup>*</sup>	114 of 158 (72%) <sup>*</sup>

\*The complements of the percentages shown in the table represent incorrect ROVER detections (i.e., ROVER gave false detections 66% (100%-34%) of the time when the pilot ratings indicated no PIO. ROVER failed to detect the presence of a PIO 9% (100%-91%) of the time when pilots encountered a PIO.

The fact that ROVER performed poorly in the absence of a PIO, a 66% false detection or nuisance rate, while maintaining an excellent positive identification rate suggested that the threshold values that ROVER used to detect PIO were set too low.

ROVER employed a set of four adjustable threshold variables to detect whether or not a PIO was present. These are repeated in Table 5-6.

Table 5-6. ROVER Threshold Values

Variable	Abbreviation	Threshold
Pitch Rate	PR	> 12 deg/sec
Elevator Deflection	ED	> 5 deg
Phase Angle	PA	> 65 deg
Pitch Rate Frequency	qF	1 to 8 rad/sec

In an attempt to isolate the problem, the detection results were examined as a function of the following factors: pilot technique, configuration, rate limit, time delay, and aggressiveness of the tracking task (i.e. Phase 2 vs. Phase 3). These detection results are shown in Tables 5-7 through 5-12 below.

Table 5-7. ROVER Detection Results - Breakout by Pilot

Pilot	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
Pilot 1	9 of 15 (60%)	31 of 34 (91%)
Pilot 2	7 of 22 (32%)	27 of 32 (84%)
Pilot 3	2 of 13 (15%)	30 of 30 (100%)
Pilot 4	0 of 3 (0%)	8 of 9 (89%)

Table 5-8. ROVER Detection Results – Breakout by Configuration

Configuration	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
Configuration A	3 of 8 (38%)	13 of 13 (100%)
Configuration B	2 of 8 (25%)	24 of 25 (96%)
Configuration C	8 of 22 (36%)	43 of 49 (87%)
Configuration D	5 of 15 (33%)	16 of 18 (89%)

Table 5-9. ROVER Detection Results - Breakout by Rate Limit

Rate Limit (deg/sec)	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
15	1 of 4 (25%)	14 of 16 (88%)
30	3 of 7 (43%)	21 of 24 (88%)
45	7 of 19 (37%)	28 of 31 (90%)
60	7 of 23 (30%)	33 of 34 (97%)

Table 5-10. ROVER Detection Results - Breakout by Time Delay

Time Delay (msec)	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
0	15 of 44 (34%)	31 of 33 (94%)
100	3 of 9 (33%)	40 of 44 (91%)
200	0 of 0 (N/A)*	25 of 28 (89%)

\*Note that all 28 of the cases with a 200 msec time delay were observed by the pilots to exhibit PIO (PIOR of 4 or higher).

Table 5-11. ROVER Detection Results - Breakout by Tracking Task

Tracking Task	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
HUD Task	15 of 45 (33%)	75 of 83 (90%)
Airborne Target	3 of 8 (38%)	21 of 22 (96%)

Table 5-12. ROVER Detection Results - Breakout by Maneuver Aggressiveness

Maneuver	ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO
Phase 2 Maneuvers	3 of 20 (15%)	58 of 60 (97%)
Phase 3 Maneuvers	15 of 33 (46%)	38 of 45 (84%)

Inspection of Tables 5-7 – 5-12 shows that ROVER had uniformly satisfactory results in correctly detecting the presence of a PIO. ROVER's poor performance when detecting the absence of a PIO, however, seemed to show a significant spread when broken-out by pilot (Table 5-7) and by the intensity of the tracking task (Table 5-12). Both tables highlight a stark difference in ROVER performance with respect to the relative intensity with which the tasks were performed.

In terms of pilot technique, the variability in ROVER's performance as shown in Table 5-7 could be largely attributed to differences in the degree of aggressiveness the pilot used during his maneuvers. To illustrate this, Figures 5-1 and 5-2 below show time histories of commanded elevator deflection angle (ED) for identical Phase 2 runs conducted by pilots 1 and 3. Both trials were HUD tracking tasks using configuration C, a rate limit of 45 deg/sec, and zero second time delay. While both pilots rated the occurrence as free from PIO (PIOR of 2), the strip charts indicated that pilot 3 was much more aggressive with his stick inputs than pilot 1. This aggressiveness of pilot 3 drove both ED and PR to exceed the ROVER thresholds (not shown), while the less aggressive pilot 1 did not. This inconsistency in pilot aggressiveness explains why ROVER correctly detected the absence of PIO four times as often for pilot 1 than for pilot 3 (see Column 2, Table 5-7). Figures B-30 and B-31 compare the power spectral density of the pilot inputs in this C configuration. It is clear from these graphs that the frequency content of pilot 3 was higher than the frequency content of pilots 1 and 2. At approximately six rad/sec, pilot 3's inputs were approximately seven dB higher than pilot 2's commanded input.

Test: HAVE ROVER Aircraft : VISTA Flight: 1 Pilot: 1  
Maneuver: Phase 2 HUD tracking task Record Number: 5 ROVER: Off

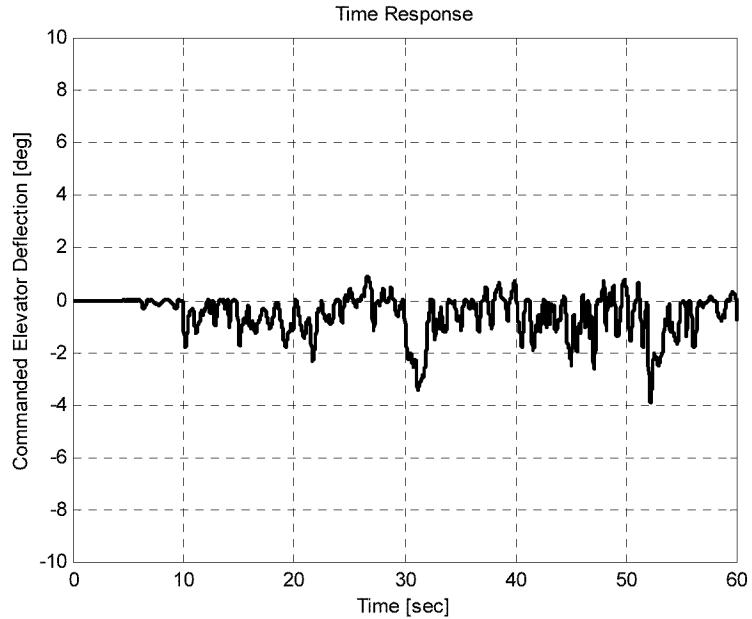


Figure 5-1. Pilot 1 - Non-aggressive Phase 2 HUD Tracking Task  
PIOR=2, RIV=2, Config C, Rate Limit 45, Time Delay 0

Test: HAVE ROVER Aircraft : VISTA Flight: 5 Pilot: 3  
Maneuver: Phase 2 HUD tracking task Record Number: 9 ROVER: Off

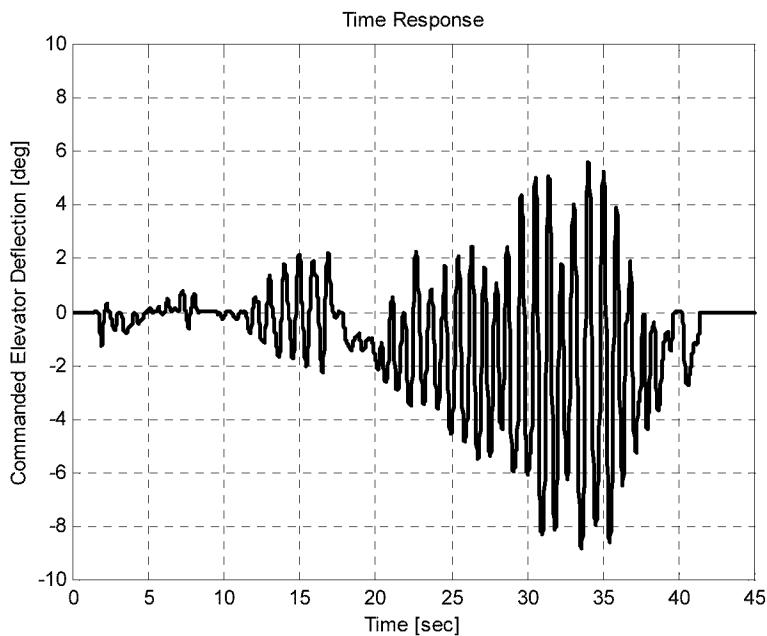


Figure 5-2. Pilot 3 - Aggressive Phase 2 HUD Tracking Task  
PIOR=2, RIV=4, Config C, Rate Limit 45, Time Delay 0

Table 5-12 further suggests that ROVER's tendency to falsely detect PIOs was related to the aggressiveness of the tracking task itself. It shows that during Phase 3 maneuvers, ROVER was three times as likely to correctly detect the absence of PIO than during more aggressive Phase 2 maneuvers. During Phase 2 maneuvers, the pilot's gains were intentionally high, so that even if the pilot observed no PIO, ROVER's thresholds were many times exceeded. Phase 3 maneuvers, on the other hand, were lower gain and much smoother. Therefore, in the absence of a PIO, ROVER's threshold values were much less likely to be exceeded. This tendency can be seen by comparing the Phase 2 results shown in Figure 5-2 above with Phase 3 data collected at the same conditions (see Figure 5-3). Figure 5-3 presents a run conducted by pilot 2 during a Phase 3 HUD tracking task with configuration C, a rate-limit of 45 deg/sec and zero second time delay. Comparison of the two figures reveals that the Phase 3 task was much less aggressive than its Phase 2 counterpart. The inherent difference in aggressiveness between Phase 2 and Phase 3 tasks explains why ROVER was able to correctly detect the absence of PIO more readily for Phase 3 maneuvers than for Phase 2.

Test: HAVE ROVER Aircraft : VISTA Flight: 2 Pilot: 2  
Maneuver: Phase 3 HUD tracking task Record Number: 19 ROVER: Off

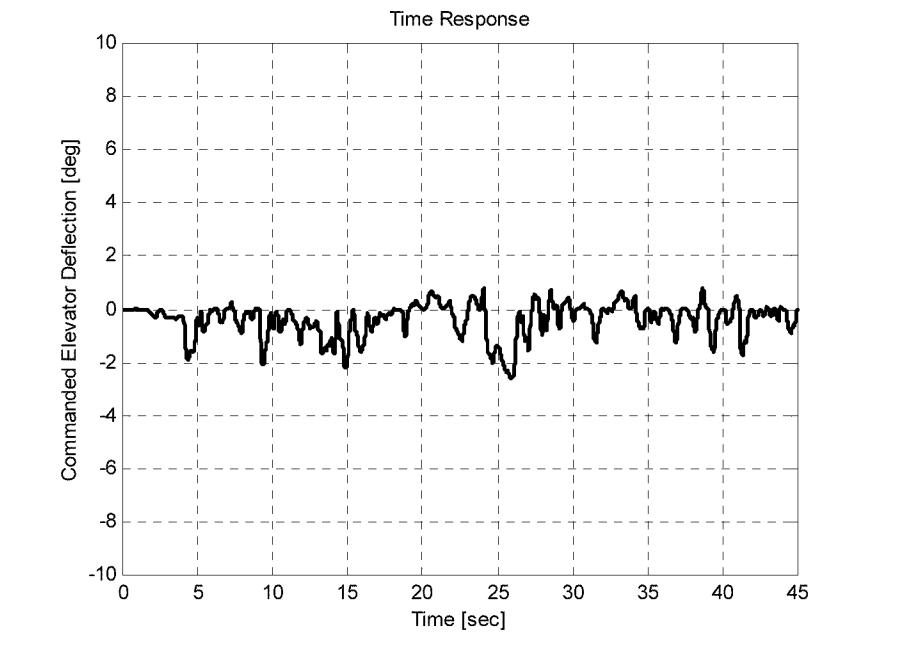


Figure 5-3. Pilot 2 – Non-aggressive Phase 3 HUD Tracking Task  
 PIOR=2, RIV=2, Config C, Rate Limit 45, Time Delay 0

In an effort to adjust the threshold values and therefore reduce ROVER's pre-disposition to false detections, a sensitivity study was conducted by varying the four threshold values shown in Table 5-6 using Phase 3 data. The results of this study are displayed in Appendix B (see Figures B-32 through B-34). The contour lines represent the percentages of correct ROVER detections for the overall detection rate (PIO present and PIO absent cases), as a function of elevator deflection, pitch rate, and phase angle.

By using the overall detection rate as the optimizing function (see Figure B-32), the detection results shown below in Table 5-13 were obtained. It should be noted that decreasing the number of false detections and increasing the number of positive detections were competing items. Therefore, it was expected to see a decrease in correct detections correlated to an increase/improvement in the false detection rate. The corresponding optimum threshold values are displayed in Table 5-14.

Table 5-13. Phase 3 ROVER Detection Results with Modified Thresholds

ROVER accuracy when the pilot did not observe a PIO	ROVER's detection rate when the pilot did observed a PIO	Overall Correct Detections
88%	76%	82%

Table 5-14. Optimized ROVER Threshold Values

Variable	Abbreviation	Threshold
Pitch Rate	PR	> 15 deg/sec
Elevator Deflection	ED	> 4 deg
Phase Angle (PR/ED)	PA	> 105 deg
Pitch Rate Frequency	qF	1 to 8 rad/sec

The combination of threshold values was chosen to maximize the correct overall detection rate (now 82%). An important note about the results presented in Table 5-13 is that the optimization function was simply an equally weighted scheme on both correct detection rate and non-PIO detection rate. An optimization scheme could be devised such that either correct non-PIO detections or correct PIO detections could be favored, or weighted, relative to the other. Such an optimization scheme based on a weighting of the respective components could be used to boost the performance of one or the other of the individual percentages in Columns 1 or 2 of Table 5-13. The relative size of the weighting coefficients could be used to control the threshold values based on the characteristics of the test configuration, tracking task, and desired correct detection rate.

Another important aspect of this study is that the optimized thresholds in Table 5-14 were derived from the aggregate of all the rate limits, airframe configurations, and time delays. It is likely that each individual configuration would have slightly different optimum threshold settings. Since each configuration represents a completely different aircraft, each could be tested and optimized based on its own PIO characteristics.

## PIO Suppression

The third objective of the HAVE ROVER project focused on the ability of the ROVER algorithm to effectively suppress PIOS during Phase 2 and Phase 3 maneuvering. EPs performed Phase 1, 2, and 3 handling qualities evaluations for each priority 1 test point in the test matrix which resulted in a PIOR of 4 or higher and a RIV of four during objective 2 tasks. The ROVER effectiveness was determined by comparing the PIOR when the ROVER logic was inactive with the PIOR when ROVER was active. Only data that had a ROVER integer value of four was compared to make sure that ROVER was able to see the PIO both when the suppression logic was active and inactive.

Table 5-15 shows the PIORs as a function of the four different project pilots (see Figures B-35 and B-36 for additional detail). Pilot 4 only had one sortie, and thus had very few data points. Three out of the four pilots found ROVER to be helpful in reducing or controlling the severity of the PIO during Phase 2 tracking. ROVER was also found to be effective in Phase 3 maneuvering. However, with pilot compensation in Phase 3 ROVER was not always reaching a RIV of four. Therefore, the filter was not activated. When ROVER made the handling qualities worse, the vast majority of these cases were due to ROVER causing a secondary PIO. When ROVER disengaged, the full, unattenuated pilot signal was sent to the flight control computer. Depending on the configuration, specifically the time delay, the pilot could instantly get a large aircraft response and get back into a PIO. This large motion/PIO was often of larger amplitude than the motion that forced ROVER to engage in the first place. This series of events often led to VSS safety trips resulting in a PIOR of 6. This sequence was highly undesirable as a bounded PIO was often driven into a larger, usually divergent PIO.

Table 5-15. ROVER PIOR Separated by Pilot

PILOT	HQ PHASE	PIOR IMPROVED WITH ROVER	PIOR DID NOT IMPROVE WITH ROVER	PIOR WORSE WITH ROVER	% PIOR IMPROVED WITH ROVER	% PIOR NOT IMPROVED WITH ROVER	% PIOR WORSE WITH ROVER
1	2	13	4	4	61.9 %	19.0 %	19.1 %
	3	8	7	1	50.0 %	43.7 %	6.3 %
2	2	12	11	1	50.0 %	45.8 %	4.2 %
	3	4	9	0	30.8 %	69.2 %	0 %
3	2	14	3	2	73.7 %	15.8 %	10.5 %
	3	8	6	1	53.3 %	40.0%	6.7 %
4	2	0	2	1	0 %	66.7 %	33.3 %
	3	0	2	1	0 %	66.7 %	33.3%
ALL	2	39	20	8	58.2 %	29.9 %	11.9 %
	3	20	24	3	42.5 %	51.1 %	6.4 %

A fadeout filter might help prevent this rapid transition between the two signals.

A filter that smoothly transitions between the attenuated, ROVER-filtered pilot command and the unfiltered pilot command could help the ROVER algorithm by preventing undesirable motion due to the switching action. This discrete jump might have been a cause in several VSS safety trips. A fadeout filter would allow the pilot's commands to be gradually input into the flight control system. This might provide the pilot with the opportunity to *feel* the aircraft response and prevent the secondary PIO. A fadeout filter would also help with the jerky movements the pilot experienced during Phase 3 maneuvering.

Table 5-16 shows the PIOR comparison separated by configuration (see Figures B-37 and B-38). ROVER was found to be significantly more helpful in A and B configurations with Phase 2 maneuvering than with Phase 3. Configurations A and B were good handling aircraft, and therefore they usually did not require outside intervention to improve aircraft performance. Configuration A's PIOR improvement percentage drastically decreased for Phase 3 maneuvering as compared to Phase 2 (from

87.5% down to 28.6%). With normal pilot compensation, low aggressiveness, and a good aircraft, the pilots often would not achieve a PIO and therefore no ROVER activation. During several trials, the pilots felt ROVER was causing some pitch bobbles due to the “jerkiness” of the activations. This is the reason that 12.5% of the Phase 2 runs were worse with ROVER. Pilots found ROVER to be slightly more helpful for Configuration B. Phase 2 maneuvering still showed a larger PIOR improvement than Phase 3, but the gap narrowed significantly (80% down to 61.5%).

Configurations C and D generated more ROVER engagements and more instances where the pilots observed ROVER deteriorating the PIOR. The overall results revealed that ROVER improved the PIOR 58.2% of the time during Phase 2 maneuvering and 42.5% during Phase 3. ROVER drove the aircraft to exhibit a worse PIOR in 11.9% and 6.4% of the trials for Phase 2 and Phase 3, respectively. Additional research in threshold optimization and applying these thresholds to specific configurations would likely improve the overall percentages and reduce the undesirable worsening performance.

Table 5-16. ROVER PIOR Separated by Configuration

CONFIG.	HQ PHASE	PIOR IMPROVED WITH ROVER	PIOR DID NOT IMPROVE WITH ROVER	PIOR WORSE WITH ROVER	% PIOR IMPROVED WITH ROVER	% PIOR NOT IMPROVED WITH ROVER	% PIOR WORSE WITH ROVER
A	2	7	0	1	87.5 %	0 %	12.5 %
	3	2	5	0	28.6 %	71.4 %	0 %
B	2	12	3	0	80.0 %	20.0 %	0 %
	3	8	5	0	61.5 %	38.5 %	0 %
C	2	16	11	3	53.3 %	36.7 %	10.0 %
	3	8	10	3	38.1 %	47.6 %	14.3 %
D	2	4	6	4	28.6 %	42.8 %	28.6 %
	3	2	4	0	33.3 %	66.7 %	0 %
ALL	2	39	20	8	58.2 %	29.9 %	11.9 %
	3	20	24	3	42.5 %	51.1 %	6.4 %

Table 5-17 shows the ROVER PIOR comparison based on the actuator rate limit (see Figures B-39 and B-40). ROVER was found to be the most beneficial for the Phase 2 handling qualities for 30 and 45 deg/sec rate limits. ROVER seemed to have little effect, either positive or negative, for the 15 deg/sec rate limit. ROVER appeared to provide some benefit for 60 deg/sec, Phase 2 handling qualities. In most cases, except for 45 deg/sec, ROVER provided very little benefit for Phase 3 handling qualities.

Table 5-17. ROVER PIOR Separated by Rate Limit

RATE LIMIT (deg/sec)	HQ PHASE	PIOR IMPROVED WITH ROVER	PIOR DID NOT IMPROVE WITH ROVER	PIOR WORSE WITH ROVER	% PIOR IMPROVED WITH ROVER	% PIOR NOT IMPROVED WITH ROVER	% PIOR WORSE WITH ROVER
15	2	2	6	2	20.0 %	60.0 %	20.0 %
	3	1	3	1	20.0 %	60.0 %	20.0 %
30	2	9	3	0	75.0 %	25.0 %	0 %
	3	3	4	1	37.5 %	50.0 %	12.5 %
45	2	14	4	2	70.0 %	20.0 %	10.0 %
	3	9	7	0	56.2 %	43.8 %	0 %
60	2	14	7	4	56.0 %	28.0 %	16.0 %
	3	7	10	1	38.9 %	55.5 %	5.6 %
ALL	2	39	20	8	58.2 %	29.9 %	11.9 %
	3	20	24	3	42.5 %	51.1 %	6.4 %

Table 5-18 shows the ROVER PIOR comparison delineated by time delay (see Figures B-41 and B-42). The most important item to note in this chart is that in ten of the eleven trials where ROVER made the aircraft PIOR worse, the time delay was 0 msec. The other case was one with 100 msec delay. In seven of these eleven, the reduction in PIOR was caused by a VSS safety trip when ROVER disengaged. This disengagement placed the pilot “back in the loop” and afforded him full authority to the flight control system. With 0 msec time delay, as soon as ROVER disengaged, the full pilot command was immediately transferred to the flight controls and often resulted in an overshoot of

the target greater than the one that caused ROVER to engage in the first place. The resulting motion was often a PIO of greater amplitude than the first PIO. For this reason, the HAVE ROVER Test Team labeled this type of motion a secondary PIO.

The other four of the eleven times where ROVER actually caused worse performance was due to the pilot encountering jerky, abrupt aircraft motion as ROVER disengaged. These jerky movements made tracking the target very difficult, and if they were significant enough, they often caused the pilot to enter a secondary PIO.

Table 5-18. ROVER PIOR Separated by Time Delay

TIME DELAY (msec)	HQ PHASE	PIOR IMPROVED WITH ROVER	PIOR DID NOT IMPROVE WITH ROVER	PIOR WORSE WITH ROVER	% PIOR IMPROVED WITH ROVER	% PIOR NOT IMPROVED WITH ROVER	% PIOR WORSE WITH ROVER
0	2	13	12	7	40.6 %	37.5 %	21.9 %
	3	6	9	3	33.3 %	50.0 %	16.7 %
100	2	17	5	1	73.9 %	21.7 %	4.4 %
	3	9	8	0	52.9 %	47.1 %	0 %
200	2	9	3	0	75.0 %	25.0 %	0 %
	3	5	7	0	41.7 %	58.3 %	0 %
ALL	2	39	20	8	58.2 %	29.9 %	11.9 %
	3	20	24	3	42.5 %	51.1 %	6.4 %

If the configuration were unstable enough (Configuration C and D), the ROVER disengagement caused an immediate VSS safety trip. Figures B-43 through B-50 show the time histories of the RIV and commanded elevator deflections for several trials. These figures cover various maneuver phases and PIOR value changes. From these figures, one can observe that ROVER attenuated the pilot commands. However, as previously discussed, as soon as the RIV decreased below four, the pilot's input immediately generated an unattenuated elevator deflection command. The only reason these commands were not immediately implemented was due to the amount of time delay

injected into the system by the configuration time delay. ROVER worked very well for Phase 2 maneuvering with 100 and 200 msec time delays but had significant difficulties when no time delay was added.

Overall, while ROVER failed to meet the objective of improving PIOR by 80%, the ROVER algorithm was found to help the pilot in suppressing PIOs, especially during Phase 2, or high gain, maneuvering. One main problem with ROVER was that it often acted as a trigger in driving the pilot from a Category II PIO into a Category III PIO. This was called a secondary PIO and often occurred as ROVER disengaged.

ROVER was not found to be especially helpful during Phase 3 maneuvering because multiple activations of ROVER only allowed the tracking error to grow larger while the pilot had little control of the aircraft. Additionally, when ROVER disengaged, it often caused the pilot to see a very quick, jerky response, especially if there were several consecutive ROVER engagements. When ROVER disengaged, the aircraft immediately responded to the full pilot command on the stick, unless delayed slightly by the simulated configuration time delay. This was why ROVER had several problems with the 0 msec time delay.

Several solutions are possible to help prevent the secondary PIOs from occurring. The first involves designing a notch filter with a more narrow attenuation band. The one implemented in this project covered the entire one to eight rad/sec band; however, a filter centered on a more narrow PIO frequency band would likely offer the pilot greater authority at the lower frequencies. He could therefore attempt to correct tracking errors even when ROVER was engaged. This narrow notch filter in conjunction with the previously mentioned fadeout filter would likely eliminate secondary PIOs.

## Pilot Performance with ROVER

To evaluate the impact of the ROVER algorithm on pilot performance, the test team evaluated three different performance parameters: 1) Cooper-Harper ratings, 2) tracking performance percentages, and 3) nuisance ratings. In each tested configuration, a Phase 3 tracking task was performed with the ROVER suppression algorithm on and off. By comparing the CHR, tracking performance, and NRs with and without ROVER, the test team was able to ascertain the impact of ROVER on task performance during the tracking tasks. To determine the confidence level of a parameters improvement, the test team calculated the mean and standard deviation of the performance between the ROVER on and ROVER off test points. Using the mean and standard deviation, the test team performed a standard student-T evaluation to get the confidence level of the mean change being greater than zero. Only confidence levels of 90% or higher were deemed statistically significant for the purposes of this project. For a normal distribution, 90% equates to approximately 1.65 times the standard deviation (2 standard deviations would be 95%).

During the evaluation of ROVER impact on task performance, the test team performed 47 Phase 3 HUD tracking tasks with ROVER on and ROVER off and 31 Phase 3 target tracking tasks with ROVER on and ROVER off. Table 22 presents the number of tracking tasks performed by each pilot.

Table 5-19. Phase 3 Data Points Evaluated

Pilot	HUD		Target	
	ROVER Off	ROVER On	ROVER Off	ROVER On
1	15	15	9	9
2	22	22	5	5
3	10	10	11	11
4	0	0	5	5
All pilots	47	47	30	30

Table 5-20 presents the overall improvement in the CHR and task performance. For the remainder of this paper, any reference to a CHR improvement is a reduction in the CH number (i.e. a 4 changing to a 3). Likewise, the mean change in CHR is actually a reduction in the number – an improvement in rating.

During the HUD tracking task, the CHR with ROVER on usually either stayed the same (55%) or improved (45%). The mean change in the CHR was almost one unit and produced a confidence level of 99%. Therefore, the test team concluded that the improvement in CHR during the HUD tracking tasks with ROVER on was statistically significant. The only other parameter to exceed the 90% level was the HUD tracking desired score parameter. With a 96% confidence level, this parameter also showed improvement with ROVER active.

The same trend could be seen in the target tracking task (same CHR – 46% and improved CHR – 38%). Due to data scatter and a low number of samples in the target tracking task, the test team concluded that the improvement in CHR, 0.29 units, was not statistically significant. (see Appendix B, Table B-1, for additional confidence level data and standard deviation values).

The required CHR improvement in the evaluation criteria for this section was a CHR improvement in 80% of the trials. ROVER did not meet the evaluation criteria for this parameter (CHR improved in only 45% of the trials for the HUD tracking task and 38% of the trials for the target tracking task). It is interesting to note that the CHR never got worse on the HUD tracking task but did get worse 17% of the time during the target tracking tasks. On the target tracking task, the mean tracking performance improvement was 2.50. Due to data scatter producing a large standard deviation, the team concluded

that this increase was not large enough to be statistically significant. The required confidence level was met for the HUD tracking task; therefore, HUD tracking performance displayed significant improvement with ROVER active.

Table 5-20. Overall Tracking Performance and CHR Improvement

Performance	Desired score		Adequate score		CHR	
	HUD	Target	HUD	Target	HUD	Target
% Improved	52	64	48	71	45	38
% Worse	29	36	32	29	0	17
% No Change	19	0	19	0	55	46
Mean Change	<b>1.52</b>	2.50	0.90	2.50	<b>0.90</b>	0.29
% Confidence	<b>96</b>	58	87	60	<b>99</b>	54

After reviewing the data, the test team concluded that these requirements for task performance and CHR improvement were not adequately balanced. The 90% confidence level for performance was a relatively lax requirement compared to the improvement in CHR at 80% of the test points. The HUD tracking mean was only improved by 1.5%. This had no direct effect on the tracking effectiveness but did meet the assigned objective. On the other hand, a reduction in CHR on 45% of the test cases was very noticeable but failed to satisfy the evaluation criteria for proving improved performance. The reduced pilot workload with ROVER active improved CHR and eliminated the pilot's need to get out of the loop. The following are typical comments made by pilot 1 during a HUD tracking task.

Table 5-21. Pilot Comments  
(Configuration B, Rate Limit 60 deg/sec, Time Delay 100 msec)

ROVER	Pilot comments
Off	If I were to stay in the loop, it would have bounced around all day. The workload was intolerable.
On	I was required to be very fine with stick inputs to get any tracking...but was not backing out of the loop. ROVER did not improve the task scores but did reduce the workload for the CHR.

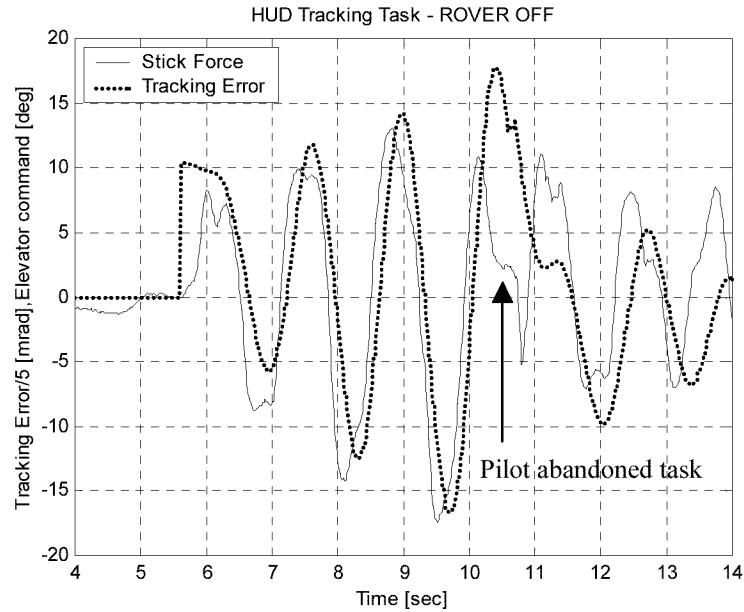
In some cases, it was clear that ROVER helped in saving the aircraft and prevented an oscillatory departure. The task, however, could not be performed because the pilot was “notched out” during large portions of the task. Therefore, task performance could not be significantly improved. The following are typical comments made by pilot 1 during an airborne target tracking task.

Table 5-22. Pilot Comments  
(Configuration C, Rate Limit 60 deg/sec, Time Delay 200 msec)

ROVER	Pilot comments
Off	Hard to stop oscillations when in the loop, very sensitive. I easily went into divergent PIO after gross acquisition...this resulted in a VSS trip.
On	ROVER engaged on initial acquisition maneuver and on numerous times after that. ROVER allowed the aircraft to be kept under control (i.e. not divergent), but it was impossible to track when ROVER was on.

Figure 5-4 presents the time history of the maneuver, which generated the pilot comments in Table 5-22. The figure shows that without ROVER, the pilot’s inputs and the tracking error were increasing until the pilot backed out of the loop for approximately half a second (time~10 sec) and then continued to track. The pilot was forced to abandon the task temporarily due to large overshoots and undesirable task performance. He assigned a CHR of 6 and a PIOR of 4 for this configuration. With ROVER on, however, ROVER engaged after one oscillation cycle thereby allowing the stability augmentation system to damp the oscillations (time~7 sec), resulting in lower workload. Even though the workload was reduced, there was no substantial impact on performance for the entire task. The pilot observed some improvement and assigned a CHR of 5 and a PIOR of 3 with ROVER on.

**Test:** HAVE ROVER    **Aircraft :** VISTA    **Flight:** 3    **Pilot:** 1    **Maneuver:**  
 Phase 3 HUD tracking task  
**Record Number:** 16    **ROVER:** Off



**Test:** HAVE ROVER    **Aircraft :** VISTA    **Flight:** 3    **Pilot:** 1    **Maneuver:**  
 Phase 3 HUD tracking task  
**Record Number:** 18    **ROVER:** On

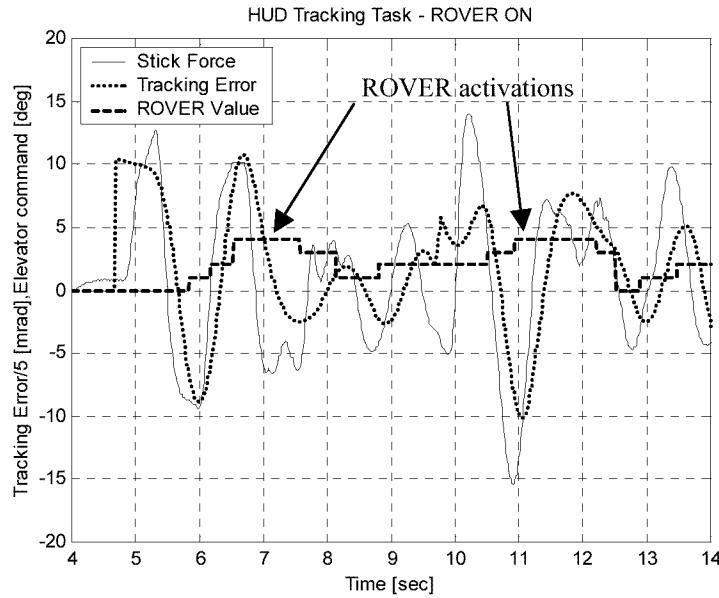


Figure 5-4. Pilot 1 - Phase 3 HUD Tracking Task with and without ROVER  
 Config B, Rate Limit 60, Time Delay 100

The effect of the test configuration on the CHR and tracking error performance is presented in Table 5-23 and in Appendix B (see Table B-2).

Table 5-23. Configuration Effect on Performance Improvement Confidence Levels

Configuration	Desired score		Adequate score		CHR	
	HUD	Target	HUD	Target	HUD	Target
A	<b>91</b>	65	89	80	82	67
B	<b>91</b>	65	89	80	82	67
C	-	64	-	68	<b>99</b>	50
D	80	-	70	-	<b>92</b>	73
All	<b>96</b>	58	87	60	<b>99</b>	54

The tracking performance improvement confidence levels in configurations A and B tended to be better than of those for configurations C and D. The test team concluded that the main cause for this trend was the longer ROVER activation times during configurations C and D. This resulted in less time in which the pilot could track that target. This in turn reduced performance. On the other hand, CHR improvement confidence levels tended to be higher in configurations C and D. Configurations C and D (poor open loop flying qualities) tended to be more prone to severe PIO, and therefore, ROVER reduced the workload required by the pilot to maintain control of the aircraft. Since tracking performance was poor in both the ROVER on and off trials, the reduction in pilot workload often lead to a slight improvement in the CHR. The ROVER on HUD tracking task in Figure 5-4 demonstrates this phenomenon. In this case, ROVER activated three times, for approximately one second each, during approximately twelve seconds of tracking time (ROVER was active 25% of the tracking time). Therefore, the

pilot was not able to track the target during a large portion of the task. Thus he had poor tracking performance but a lower workload than the similar ROVER off trial.

The effect of rate limiting on the CHR and tracking error performance is presented in Table 5-24 and Table B-3. The mean improvement in tracking performance in the HUD tracking task at 15 deg/sec was negative, which equates to deterioration in performance. This result corresponds to a similar trend shown in the configuration effect in which aircraft with high PIO tendencies resulted in reduced performance due to long ROVER activations. This reduced the effective pilot tracking time. In the HUD tracking task, the mean improvement in the CHRs in configurations with 15 and 30 deg/sec rate limits (1.75 and 1.57, respectively) was higher than the mean improvement in configurations with 45 and 60 deg/sec rate limits (0.38 for both). However, due to the associated standard deviations, all but the 15 deg/sec configurations were deemed statistically significant. It is also noteworthy to highlight the two items in the desired score column which exceeded the 90% level. The high mean change for the 30 deg/sec configuration produced a 92% confidence level. Additionally, the overall mean change for all rate limits had a 1.52 mean improvement. This, however, produced the highest confidence level of all even though it incorporates the negative value at the top of the column (-2.50 mean change for 15 deg/sec). The primary factor here is the sample size. Because the aggregate has more than 30 samples, the student-T essentially becomes a normal distribution where confidence levels are easier to achieve.

Table 5-24. Rate Limit Effect on Tracking Performance and CHR Improvement

Rate limit (deg/sec)	Performance	Desired score		Adequate score		CHR	
		HUD	Target	HUD	Target	HUD	Target
15	Mean Change	-2.50	4.50	-3.25	1.00	1.75	0.00
	% Confidence	-	57	-	53	86	-
30	Mean Change	<b>3.71</b>	9.00	1.29	10.33	<b>1.57</b>	-0.50
	% Confidence	<b>92</b>	75	74	86	<b>96</b>	-
45	Mean Change	1.63	1.17	1.63	0.67	<b>0.38</b>	0.75
	% Confidence	84	55	88	53	<b>90</b>	72
60	Mean Change	1.63	-2.67	1.63	-0.67	<b>0.38</b>	0.33
	% Confidence	84	-	88	-	<b>90</b>	58
All	Mean Change	<b>1.52</b>	2.50	0.90	2.50	<b>0.90</b>	0.29
	% Confidence	<b>96</b>	58	87	60	<b>99</b>	54

The main reason why the target tracking tasks showed no marked improvement was multiple VSS trips during the gross acquisition, which, by definition, resulted in CHRs of 10. At low rate limits during the gross acquisition, the rate limit would be met. In the “bad” configurations (C and D), the maneuver would result in a quick VSS safety trip. ROVER was implemented as a reactive device; therefore, it was often unable to observe and suppress the motion prior to the predictive VSS trip. This trend would also explain the lower confidence levels in CHR improvements in configurations C and D (see Table 5-23). Pilot 1 made the following comments during a target tracking task.

Table 5-25. Pilot Comments  
(Configuration D, Rate Limit 15 deg/sec, Time Delay 0 msec)

ROVER	Pilot comments
Off	Phase 3 initial fine tracking was good, but an abrupt gross acquisition from lag caused an oscillation that diverged rapidly on the 3 <sup>rd</sup> oscillation resulting in a VSS trip.
On	Phase 3 ROVER on, overshoot on a gross acquisition from lag resulted in divergence and a VSS trip almost as soon as ROVER activated. An earlier activation of ROVER would have helped here.

Figure 5-5 presents the time history of the maneuver that precipitated the comments in Table 5-25. In Figure 5-5, the HUD tracking task generated a 100-mrad error (at time~49 sec). The pilot tried to aggressively reduce the error, which resulted in pitch rates of approximately 20 deg/sec, an elevator rate limit, and a VSS trip (at time ~51 seconds). Note that ROVER was on and filtering pilot command for approximately one second prior to the VSS trip but could not prevent the trip.

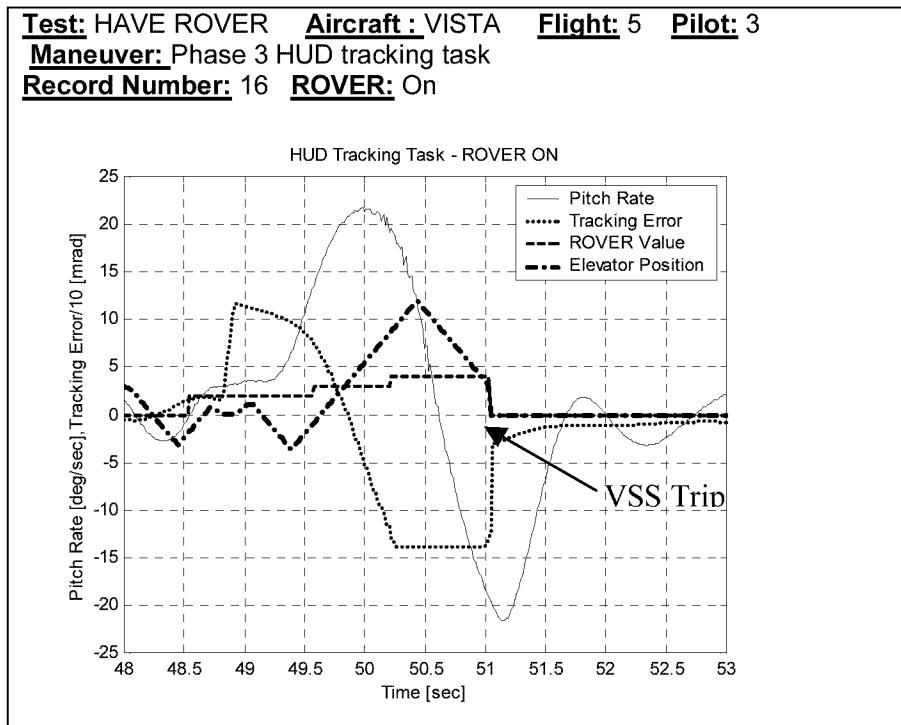


Figure 5-5. Pilot 3 - Phase 3 HUD Tracking Task with ROVER on  
 Config D, Rate Limit 15, Time Delay 0

The effect of time delay on the CHR and tracking error performance is presented in Table 5-26, Table 5-27, and Table B-4. The CHR improvement in all HUD tracking tasks exceeded the 90% level; therefore, the test team concluded that ROVER did improve the CHR for HUD tracking tasks in all time delay configurations. The CHR improvement in the target tracking task was better during the 200 msec time delay configuration than any other configuration but still was not deemed a statistically significant improvement.

Table 5-26. Time Delay Effect on CHR Improvement

Performance	Time Delay 0 msec		Time Delay 100 msec		Time Delay 200 msec		Time Delay All	
	HUD	Target	HUD	Target	HUD	Target	HUD	Target
% Improved	<b>44</b>	36	<b>57</b>	24	<b>25</b>	60	<b>45</b>	38
% Worse	<b>0</b>	18	<b>0</b>	13	<b>0</b>	20	<b>0</b>	17
% Same	<b>56</b>	45	<b>43</b>	63	<b>75</b>	20	<b>55</b>	46
Mean Change	<b>1.56</b>	0.55	<b>0.79</b>	-0.38	<b>0.38</b>	0.80	<b>0.90</b>	0.29
% Confidence	<b>95</b>	58	<b>99</b>	-	<b>90</b>	68	<b>99</b>	54

The highest performance improvement confidence level was achieved at 100 msec for the HUD tracking task and at 200 msec for the target tracking task. The optimal improvement was achieved at the same conditions in which optimal CHR improvements were achieved. Based on pilot comments and observations as well as the meager results shown in Table 5-27, the test team concluded that ROVER did not have a significant effect on performance for the time delay configurations. ROVER did, however, significantly improve the CHRs through reduced pilot workload.

Table 5-27. Time Delay Effect on Tracking Performance

Time Delay	Performance	Desired score		Adequate score	
		Improvement	HUD	Target	HUD
0 msec	Mean Change	1.78	0.57	0.00	2.00
	% Confidence	78	52	50	58
100 msec	Mean Change	<b>1.79</b>	5.25	<b>1.86</b>	2.25
	% Confidence	<b>97</b>	64	<b>95</b>	56
200 msec	Mean Change	0.75	3.33	0.25	4.00
	% Confidence	69	70	58	74
All time delays	Mean Change	<b>1.52</b>	2.50	0.90	2.50
	% Confidence	<b>96</b>	58	87	60

From the analysis presented in the PIO Detection section, it is clear that the ROVER algorithm, with the current threshold values, was very prone to Type 3 nuisance ratings. As detailed in Figure C-3, this is when ROVER characterizes the oscillation as a severe PIO when the pilot did not. The ROVER accuracy when the pilot did not observe a PIO was only 46% (see Table 5-12). On 54% of all of the Phase 3 tasks, the pilot did not feel there was a PIO, but the RIV was four. Nuisance activations took control of the aircraft and adversely effected task performance. Nuisance activations at a rate over about 10% of the time will likely force pilots into ignoring warning messages or disabling the system altogether. Further research in the area of threshold optimization might improve ROVER performance to operationally acceptable levels. The following comments were made by pilot 3 during a HUD tracking task.

Table 5-28. Pilot Comments  
(Configuration C, Rate Limit 60 deg/sec, Time Delay 0 msec)

ROVER	Pilot comments
Off	Small/mild bobbles, but no significant oscillations, while fine tracking. PIO rating of 2.
On	Gross acquisition/aggressive pulls drove “PIO” [a ROVER activation] but I felt I was still in phase with aircraft response. (Nuisance Rating of 3).

## Arriving at a RIV of Four

Careful examination of Figure 5-5 reveals the incremental build-up in ROVER value. The scale is expanded so that the transition from a RIV of zero to a RIV of four occurs in only two seconds. At 48.5 sec, RIV jumps from zero to two followed by a step to three approximately one second later. The transition is complete just after 50 seconds when the RIV steps up to four. Most trials displayed a similar build-up to the maximum value of four and then the associated filtering of pilot commands. The most significant difference between ground simulation and flight test data was the order in which the build occurred. During ground simulations, the DE and PR conditions were usually met quickly at the beginning of the task. The qF condition was met as soon as the oscillation developed, so the RIV quickly jumped to a three at the start of the trial. Nearly without exception, the PA condition was the last one to be satisfied. Because of this characteristic, the PA condition received a tremendous amount of attention during early experimental research. This was also the foundation for using a PA of 65 as the starting threshold for flight test as 65 deg appeared to be a reasonable tradeoff between nuisance activations and early detection. Figure 5-6 shows a Simulink<sup>®</sup> simulation result where the PA condition varies around 50 deg but does not exceed the 65 deg threshold until approximately eight seconds into the trial. At this point, all conditions have been met driving the RIV to a four (DE, PR, and qF conditions not shown).

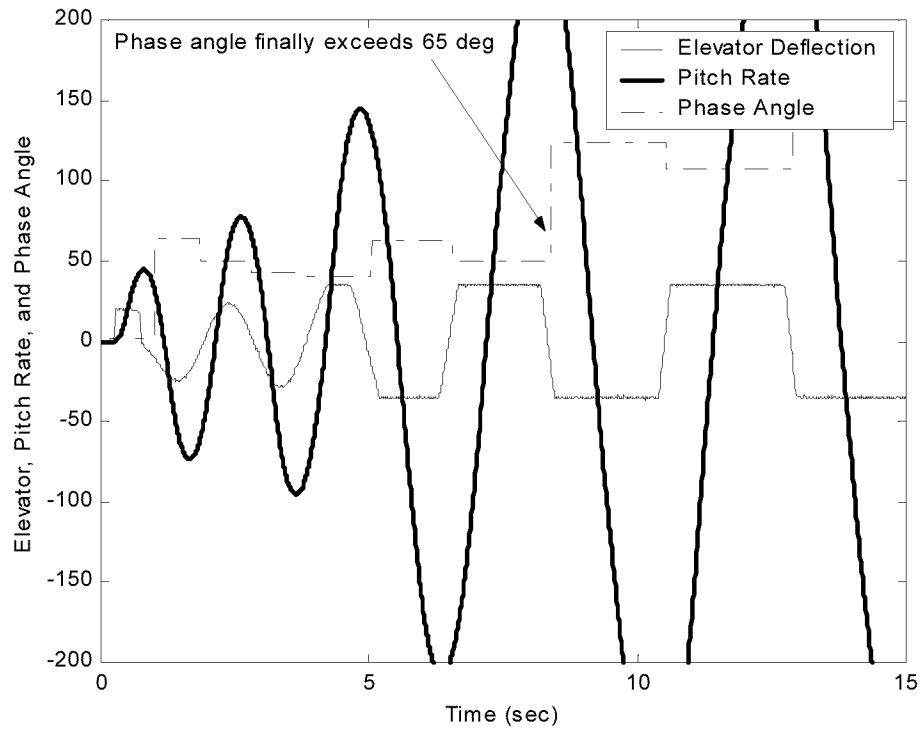


Figure 5-6. Simulink® Simulation of PA Buildup  
Config C, Rate Limit 60, Time Delay 0

Flight test data, on the other hand, revealed a surprisingly different characteristic. As seen in Figure 5-7, PA and qF were met at the beginning of the trial resulting in a RIV of two until nearly the 22 second point. Flight test trials, unlike the ground simulation, depended more upon the DE and PR conditions. These conditions can be seen ramping up and exceeding the preset thresholds at approximately 22 seconds. At that time the PA condition momentarily drops below the 65 deg threshold and then again exceeds it. The RIV finally reaches four just after the 27-second point. The earlier established build-up in phase angle difference did not occur as it did during the ground tests. The most reasonable answer to the question why is because of the simple pilot model used during ground simulation. This simple pilot model discussed in Chapter 2 provided proportional

gain to the error signal. In flight, the test pilots were much more complicated and compensating. Obviously, the flight test data is the truth source. The optimization study detailed earlier in this chapter strongly supports the historical studies done by Mitchell and suggests that the PA condition should be set around 105 degrees. While each condition is important, future projects should put more emphasis on the DE and PR conditions and realize that an optimal solution can only truly optimize the performance of a single configuration.

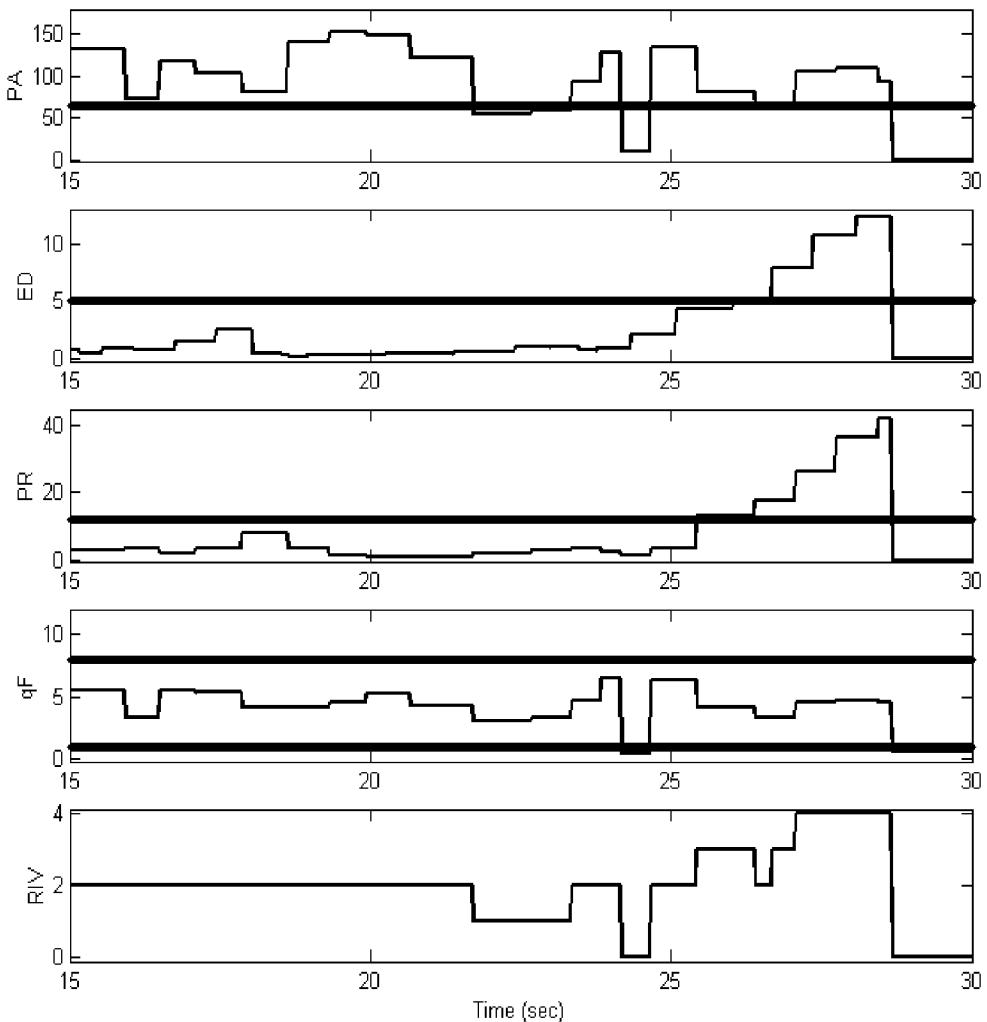


Figure 5-7. Flight Test Data of PA Build-up

## **Handling Qualities with ROVER**

One problem observed but not directly investigated in this project was that all configurations offered extremely poor low frequency authority during ROVER activations. Figure 2-1 shows that at approximately 0.3 rad/sec, the attenuation is approaching 3dB. This equates to half of the command being attenuated at a command frequency as low as 17 deg/sec. The effect of this was that it prevented the pilot from reducing tracking errors while the notch filter was active. In order to avoid ground contact, low frequency authority would be critical during low altitude PIOs. This authority would also be crucial in an attempt to maneuver the aircraft away from threats during aerial combat. Additional research should directly investigate low frequency authority available to the pilot during ROVER activations. Implementation of a narrow notch filter will likely improve command authority during ROVER activations. A more effective filter could be designed around the open loop short period frequency or any known or observed PIO frequency.

## VI. Conclusions and Recommendations

This thesis detailed the development and verification of a real-time oscillation verifier algorithm and accompanying notch filter on pilot longitudinal commands. It improved upon previous designs by operating real-time vice in a post-processing mode. Additionally, this project explored both rate limiting and time delay PIO events.

### ROVER PIO Detection

With the original threshold settings, the ROVER algorithm correctly characterized pilot observations of the aircraft motion 72% of the time. Further analysis indicated that a high false detection rate was responsible for this relatively low overall correct detection rate. When pilots observed no PIO, ROVER agreed only 34% of the time. However, when pilots perceived there to be a severe PIO, ROVER agreed 91% of the time. These results suggested that the threshold values used by ROVER to detect PIO were set too low. This was corroborated by the fact that correct characterizations of non-PIO maneuvers were much less likely for aggressive maneuvers than for non-aggressive maneuvers. By varying the threshold values as part of a parametric study, a maximum overall correct detection rate of 82% was attained. While the false detection rate was cut to 14% (from 66%), ROVER's correct identification of actual PIOs was also reduced to 76% (from 91%). An appropriate tradeoff could be made using a weighting function to emphasize either false or correct detections during the optimization process. Although such an optimization might result in a somewhat lower overall correct detection rate, the fractions attributed to false alarms and correct PIO detections could be adjusted.

Such a procedure could also be used to examine the effect of individual aircraft configurations on the threshold values. The optimal thresholds determined using the HAVE ROVER flight test data simply provide a good reference point for future research. While producing an overall correct detection rate of 82%, the solution is not robust for all aircraft and does not necessarily represent an optimal solution for any aircraft configuration.

## **ROVER PIO Suppression**

Overall, while ROVER did not meet the objective of improving PIOR by 80%, the ROVER algorithm was found to help the pilots in suppressing PIOs, especially during Phase 2, or high gain, maneuvering. ROVER was somewhat helpful during Phase 3 maneuvering, or compensatory tracking. This was due to the fact that when ROVER disengaged, it often caused the pilot to see a very quick, jerky response, especially if there were several consecutive ROVER engagements. The main problem with ROVER being able to suppress a PIO was found to be due to the pilot getting into a secondary PIO when ROVER disengaged.

This project intended to examine Category II (linear with some nonlinear event) PIOs (see Chapter 1). Instead, the test team encountered several Category III PIOs (complex nonlinearities with complex transitions) in the form of secondary PIOs. This phenomenon was beyond the scope of the test plan and severely complicated the statistical analysis. Since ROVER's performance was generally much better for the Category II PIOs and often caused the Category III PIOs, more research is warranted.

ROVER must be modified to improve Category II PIO suppression and to eliminate Category III PIO transitions.

### **Pilot Performance with ROVER**

Three performance parameters were evaluated during the test: Cooper-Harper Ratings (CHRs), tracking performance, and nuisance ratings (NRs). CHRs were shown to have statistically significant improvement during HUD tracking tasks. This improvement was independent of rate limit, time delay, pilot, and pilot aggressiveness. CHRs improved on 45% of the HUD tasks and 38% of the target tracking tasks. These results did not meet the 80% improvement required by the evaluation criteria in the test plan.

Although ROVER did not meet the evaluation criteria, the improvement in CHRs was noticeable and was mainly attributed to reduction in pilot workload in maintaining aircraft control. The CHR improvement mainly occurred in the PIO-prone configurations (configurations C and D and rate limits of 15 and 30 deg/sec). These configurations demanded high pilot work load to maintain aircraft control. The CHR improvement during the HUD tracking tasks (improvement demonstrated to a 99% confidence level), was much more pronounced than during target tracking tasks (no statistically significant improvement shown). The main cause for this trend was VSS safety trips during gross acquisition. ROVER was implemented as a reactive algorithm, and therefore often did not have time to observe and suppress the motion prior to some VSS trips.

The HUD task tracking performance improved by 1.5 with 96% confidence level while the target tracking task performance improvement of 2.5 was not statistically significant due to a large standard deviation. Although ROVER met the evaluation

requirements for tracking performance improvement in the HUD tracking task, the test team felt ROVER had minimal effect on the tracking effectiveness in both the HUD tracking task and the target tracking task. ROVER tended to have worse tracking performance for configurations that were more prone to PIO. This was due to very long ROVER activations times. During ROVER activations, the pilot was not able to reduce the tracking error between the pipper and the target.

### **Additional Observations**

One problem observed but not directly investigated in this project was that all configurations offered extremely poor low frequency authority during ROVER activations. This prevented the pilot from reducing tracking errors while the notch filter was active. Future projects should investigate low frequency authority available to the pilot during ROVER activations. A possible solution to this low frequency attenuation is to implement a narrower notch filter. A more effective filter could be designed around the open loop short period frequency or any known/observed PIO frequency.

As mentioned in Chapter 3 during the Min\_Max Logic section, the tremendous amount of filtering performed on the raw signals prior to determining the seven critical parameters created a time delay within the ROVER algorithm. While ground simulation results appeared unaffected by this nearly 0.5 second decision time induced by the fourth order noise filter, flight test results highlighted this undesirable trait. This half second delay between when the pilot felt a PIO and when ROVER actual engaged occasionally resulted in negative pilot comments. Severe filtering is going to be critical to the effective operation of ROVER; however, a filter that induces less time delay is desired.

The overall performance of ROVER supported the earliest ideas about ROVER. If implemented correctly, ROVER will help prevent severe PIOs and oscillatory departures, but it cannot turn a poor handling aircraft into a good tracking aircraft. It is simply a safety device to allow pilots to safely recover an aircraft after a potentially life threatening, catastrophic PIO event.

## Appendix A: Matlab Files

### **PIOsim.m** MATLAB™ file from Hoh Aeronautics, Inc. for PIO severity determination

```
%-----1-----2-----3-----4-----5-----6-----7-----  
8  
% 'PIOsim.m'  
%  
% Program to examine pio filter and solve for state transition  
parameters.  
% Reads a data file, sets up filters for I/O (stick force and pitch  
rate),  
% and extracts dominant frequency and phase lag on a frame-to-frame  
basis  
% in order to examine potential PIO detection and measurement  
strategies.  
% This routine is a translation of existing Fortran code that can be  
more  
% easily studied and modified.  
  
% Author: R. Heffley 10 Mar 1998 Original translation from Fortran PIO  
program.  
% Revised: 1 Aug 1998 Clean up of I/O and addition of DGM  
pio flags.  
%  
%-----o-----o-----o-----o-----o-----o-----o-----  
o  
  
clear  
  
%*****  
*  
% A Setup analysis by reading data, defining filter and PIO parameters:  
  
% 1 Name and read data file  
% (from prior extraction using a Fortran data read program):  
  
filename = input('Enter filename > ','s');  
% fid = fopen(filename,'rt');  
  
% filename= ';  
% eval(filename)  
  
% 2 Define t, Fe, q, and nz in data array:  
t = timeT; % time (reconstructed evenly-spaced time vector)  
Fe = PIOdata(:,2); % stick force  
q = PIOdata(:,3); % pitch rate  
nz = PIOdata(:,4); % normal accel  
  
% 3 Set PIO discrimination parameters:  
delTf = .10; % min time between extremes  
delAf = 0.1; % value for real stick force  
delTq = 0; % min time between extremes  
delAq = 0.2;  
fullCycle = 0; % flag to set full cycle calculation of freq, phase
```

```

        % (default is half-cycle calculation)

% 4 Set PIO flag parameters:
wMin = 1;
wMax = 8;
phMin = 75;
phMax = 360;
qMax = 12;
% DGM 8/26/99: try FMax = 1.5 instead of 2
FMax = 1.5;

% 5 Define filter characteristics
zeta=.5;           % damping ratio of filter poles
% DGM 8/26/99: try wCtr = 3.5 instead of 3.2
wCtr=3.5;          % bandpass center frequency
wDel=3.;           % half-width of bandpass

%***** ****
*
% B Prepare for processing a run (could be a real-time run):

% 1 Setup discrete filter:
% filter break frequencies, damping
z1=zeta; w1=wCtr-wDel;
z2=zeta; w2=wCtr+wDel;

nFilt=[1 0 0];    % two free s zeros
dFilt=conv([1/w1^2 2*z1/w1 1],[1/w2^2 2*z2/w2 1]); % convolve poles

amp=bode(nFilt,dFilt,wCtr);    % amplitude at peak
Kfilt=1/amp;          % adjustment to make peak amplitude unity
sys1=tf(Kfilt*nFilt,dFilt); % this is filter LTI

% filtered pitch rate
qF=lsim(sys1,q,t);    % time history of filtered signal (to display)

% set up discrete filter
[a,b,c,d]=tf2ss(Kfilt*nFilt,dFilt);
sys2=ss(a,b,c,d); % state space LTI
T=t(2)-t(1);        % delta t
sys3=c2d(sys2,T); % continuous to discrete transformation
[A,B,C,D]=ssdata(sys3);

% 2 Initialize for time solution:
[nn,nSteps]=size(t);
[ordr oo]=size(A);
xf=zeros(ordr,1);
xq=zeros(ordr,1);

Fmax1=0; Fmax2=0; Fmin1=0; Fmin2=0; Ftrend='up';
tFmax1=-1; tFmax2=0; tFmin1=-1; tFmin2=0;
fF0=0; fF1=0;          % last qF
Ftrigger = 0;
divF=0;

Qmax1=0; Qmax2=0; Qmin1=0; Qmin2=0; Qtrend='up';
tQmax1=-1; tQmax2=0; tQmin1=-1; tQmin2=0;

```

```

qF0=0;qF1=0;           % last qF
Qtrigger = 0;
divQ=0;

ph=0;
wAv=0;
PIOseverity=0;
phLast=0;
wAvLast=0;
PIOlast=0;
plotArray=[];      % [Time,ph,wAv,divF,divQ, ...
% (Fmax2-Fmin2)/aAv, (Qmax2-Qmin2)/aAv, ...
%
PIOseverity,flag_omega,flag_phase,flag_q,flag_stick]
plotArra2=[];      % [Time, xPastUp, xPastDn]
plotArra3=[];      % [Time, xPastUp, xPastDn]

%***** ****
*
% C Process frame-by-frame:

% ----- START FRAME -----
% 1 Begin real-time frame:
for i=1:nSteps
    Time= t(i);

% 2 Calculate filter output:
    uf = Fe(i);
    xf = A*xf + B*uf;
    yf = C*xf + D*uf;
    FeFd(i)=yf(1,1);

    uq = q(i);
    xq = A*xq + B*uq;
    yq = C*xq + D*uq;
    qFd(i)=yq(1,1);

% 3 ID max/min features using function 'idWave':
    fF1 = FeFd(i);

    [Ftrend,Fmax1,Fmax2,Fmin1,Fmin2,tFmax1,tFmax2, ...
     tFmin1,tFmin2,Ftrigger,plotArra2] ...
    = idWave(fF0, fF1,Time,delTf,delAf,Ftrend, ...
              Fmax1,Fmax2,Fmin1,Fmin2, ...
              tFmax1,tFmax2,tFmin1,tFmin2, ...
              2,Ftrigger,plotArra2,'b');

    qF1 = qFd(i);

    [Qtrend,Qmax1,Qmax2,Qmin1,Qmin2,tQmax1,tQmax2, ...
     tQmin1,tQmin2,Qtrigger,plotArra3] ...
    = idWave(qF0, qF1,Time,delTq,delAq,Qtrend, ...
              Qmax1,Qmax2,Qmin1,Qmin2, ...
              tQmax1,tQmax2,tQmin1,tQmin2, ...
              2,Qtrigger,plotArra3,'r');

% 4 Calculate pio features:
if Qtrigger>0
    tF1 = tFmax2-tFmax1;

```

```

tF2 = tFmin2-tFmin1;
tF3 = 0.5*(tF1+tF2);

tQ1 = tQmax2-tQmax1;
tQ2 = tQmin2-tQmin1;
tQ3 = 0.5*(tQ1+tQ2);

% 5 Compute q-F time shift and period of waveform:
    if Qtrend=='dn', dtAv = tQmax2-tFmax2; end % average time shift
of max pts
    if Qtrend=='up', dtAv = tQmin2-tFmin2; end % average time shift
of min pts

    if fullCycle==1 % use full-cycle estimation of period tAv
        if Qtrend=='dn', tAv = (tQmax2-tQmax1);end      % time based on
Q only
        if Qtrend=='up', tAv = (tQmin2-tQmin1);end      % time based
on Q only
    else % use half-cycle estimation
        if Qtrend=='dn', tAv = (tQmax2-tQmin2)*2;end % time based on Q
only
        if Qtrend=='up', tAv = (tQmin2-tQmax2)*2;end % time based on Q
only
    end
    wAv = 6.28/tAv;      % average frequency (rad/sec)
    ph = dtAv/tAv*360; % phase shift (deg)

% 6 Set PIO flags (based on DGM simplified logic):
flag_omega=0;          % initialize flags to off
flag_phase=0;
flag_q=0;
flag_stick=0;

w_q = wAv;            % frequency
ph_qf = ph;          % phase lag

% DGM: for now, rectify pk values at wAv using sys1 (continuous
filter).
%
aAv = bode(sys1,wAv);

if ((wMin < w_q) & (w_q < wMax)), flag_omega=1; end
if ((phMin < ph_qf) & (ph_qf < phMax)), flag_phase=1; end
if ((Qmax2-Qmin2)/aAv > qMax), flag_q=1; end
if ((Fmax2-Fmin2)/aAv > FMax), flag_stick=1; end
PIOlast = PIOseverity;
PIOseverity = flag_omega + flag_phase + flag_q + flag_stick;

% DGM 6/21/99: Make special setting if either omega or phase
not in range

if ((PIOseverity == 3) & (flag_omega == 0)),
PIOseverity=2.5; end
if ((PIOseverity == 3) & (flag_phase == 0)), PIOseverity=2.5; end

% DGM 6/21/99: Make another setting if last sample was a 2.5
or 3

```

```

        if ((PIOseverity == 2.5)&(PIOlast == 2.5)),  

        PIOseverity=3.5; end  

        if ((PIOseverity == 2.5)&(PIOlast == 3)), PIOseverity=3.5; end  

        if ((PIOseverity == 3)&(PIOlast == 2.5)), PIOseverity=3.5; end  

        if ((PIOseverity == 3)&(PIOlast == 3)), PIOseverity=3.5; end  

        % End of DGM changes 6/21/99  

% 7 Compute divergence of states:  

if Fmax1~=0 & Fmin1~=0,divF = (Fmax2-Fmin2)/(Fmax1-Fmin1);end  

if Qmax1~=0 & Qmin1~=0,divQ = (Qmax2-Qmin1)/(Qmax1-Qmin1);end  

% 8 Store everything from plotting:  

plotArray = [ plotArray;  

              [Time,ph,wAv,divF,divQ, ...  

               (Fmax2-Fmin2)/aAv,(Qmax2-Qmin2)/aAv,PIOseverity, ...  

               flag_omega,flag_phase,flag_q,flag_stick]  

            ];  

end % of Qtrigger set  

% 9 Update past values  

qF0=qF1;  

fF0=fF1;  

phLast = ph;  

wAvLast = wAv;  

divQlast=divQ;  

divFlast=divF;  

Ftrigger=0;  

Qtrigger=0; % reset if tripped  

% ----- END FRAME -----  

end  

*****  

*  

% D Plot the final results for this run:  

drawPIO(filename,sys1,t,q,Fe,nz,qFd,FeFd,plotArray,plotArra2,plotArra  

3)  

% DGM 6/21/99: Also save plotArray (has all key info) to a file:  

ext = '_out.txt';  

fileout = [filename,ext];  

save(fileout,'plotArray','-ASCII');  

% end of 'PIOsim.m'  

%-----1-----2-----3-----4-----5-----6-----7-----  

8

```

**PIOsetup.m** MATLAB™ file from Hoh Aeronautics, Inc. to generate the necessary m-file for PIOsim

```
%-----1-----2-----3-----4-----5-----6-----7-----  
8  
% 'PIOsetup.m'  
%  
% Converts time history file from HAI PIO sim for PIO analysis  
% DGM 16 Feb 99  
%-----o-----o-----o-----o-----o-----o-----o-----  
o  
  
clear  
  
%*****  
*  
% A Setup file by reading data  
  
% 1 Name and open data file  
  
% filename= 'a0408051';  
filename = input('Enter filename > ','s');  
fid = fopen(filename,'rt');  
  
% 2 Read variable names (row 1 of file)  
  
Vars = fscanf(fid,'%14c',[1,40]);  
  
% 3 Read all numbers to end of file; Cnt is counter for total # read  
  
THdata = fscanf(fid,'%g',[40,inf]);  
  
% 4 Transpose matrix, determine number of rows, endtime, deltatime  
  
THdata=THdata';  
THsize = size(THdata);  
Nrows= THsize(1,1);  
tEnd = THdata(Nrows,1);  
deltaTime = tEnd/Nrows;  
  
% B Write data to output file  
  
% 1 Create file  
  
ext = '.m';  
fn = [filename,ext];  
comment =['% '];  
caseid = [comment, filename];  
fido = fopen(fn, 'w');  
  
% 2 Force header info as required  
  
fprintf(fido,'%s',caseid, '    HLON = ');  
fprintf(fido, ' %7.3g',THdata(1,34));  
fprintf(fido, '    HLAT = ');  
fprintf(fido, ' %7.3g',THdata(1,35));  
variables = [comment, 'TIME' STICKLON(1) PITCHQ  
NZ'];  
fprintf(fido, '\n%s', variables);
```

```

fprintf(fido, '\nPIOdata = [ ...');

% 3 Write time-history data
%   Write entire file from 1-sec point on (if less than full run) or
thru task
%   Task starts at t = 10 sec (row 601) and runs till 137.6 sec (row
8256), add 2 sec each side
%   Have to limit file sizes so take every other time slice (.032
sec/slice)

iStart = 481;
iEnd = 8376;
iRows = iEnd;
if Nrows < iEnd;
    iRows = Nrows-1;
end
for i = iStart:2:iRows;
    Time(i) = THdata(i,1) - THdata(481,1);
    fprintf(fido, '\n %14.7g      %14.7g      %14.7g      %14.7g',
Time(i),THdata(i,4),THdata(i,6),THdata(i,9));
end

% 4 Force footer info as required

fprintf(fido, '\n] ;');
fprintf(fido, '\n[n1,n2]=size(PIOdata)');
fprintf(fido, '\naverageDeltaT=');
fprintf(fido, '%14.7g', deltaTime*2);
fprintf(fido, '\ntimeT=linspace(');
fprintf(fido, '%14.7g, %14.7g,n1)', Time(1), Time(i));
p1 = ['plot(timeT,PIOdata(:,2),''r''),hold on'];
p2 = ['plot(timeT,PIOdata(:,3),''b'')'];
p3 = ['plot(timeT,PIOdata(:,4),''g'')'];
p4 = ['axis([1 60 -10 20])'];
fprintf(fido, '\n%s \n%s \n%s \n%s', p1, p2, p3, p4);

% 5 Close file

fclose(fido);
disp(['HLON = ',num2str(THdata(1,34))])
disp(['HLAT = ',num2str(THdata(1,35))])
disp(['End time = ',num2str(Time(i))])

% C End

%-----1-----2-----3-----4-----5-----6-----7-----
8

```

***idWave.m* MATLAB™ file from Hoh Aeronautics, Inc. to find peaks in time responses**

```
function [trend,Xmax1,Xmax2,Xmin1,Xmin2,Tmax1,Tmax2, ...
    Tmin1,Tmin2,trigger,plotArraX] ...
= idWave(xPast,x,Time,delT,delA,trend,Xmax1,Xmax2,Xmin1,Xmin2, ...
    Tmax1,Tmax2,Tmin1,Tmin2,fig,trigger,plotArraX,color)

% ID max:
if trend=='up' ...
    & x <= xPast ...
    & Time - Tmax2 > delT ...
    & x > delA

    Xmax1 = Xmax2; % update new pt
    Tmax1 = Tmax2; % ...and respective time
    Xmax2 = xPast; % update prior pt
    Tmax2 = Time; % ...and respective time
%
    disp([1 Tmax1 Tmax2])
    trend='dn'; % switch trend
    trigger = 1; % set trigger variable
%
    figure(fig),subplot(2,1,1),plot(Time, xPast, ['*' color]),hold
on
    plotArraX=[plotArraX;[Time,xPast,-999]];
end

% ID min:
if trend=='dn' ...
    & x >= xPast ...
    & Time - Tmin2 > delT ...
    & x < delA

    Xmin1 = Xmin2; % update new pt
    Tmin1 = Tmin2; % ...and respective time
    Xmin2 = xPast; % update prior pt
    Tmin2 = Time; % ...and respective time
%
    disp([2 Tmin1 Tmin2])
    trend = 'up'; % switch trend
    trigger = 2; % set trigger variable
%
    figure(fig),subplot(2,1,1),plot(Time, xPast, ['o' color]),hold
on
    plotArraX=[plotArraX;[Time,999,xPast]];
end
return
```

**drawPIO.m** MATLAB™ file from Hoh Aeronautics, Inc. to generate summary plots

```
function drawPIO(filename,sys1,t,q,Fe,nz,qFd,FeFd, ...
plotArray,plotArra2,plotArra3)
%-----1-----2-----3-----4-----5-----6-----7-----
8
%   'drawPIO.m'
%
% Subroutine to draw plots resulting from 'PIOsim'.
%
% Author: R. Heffley 1 Aug 1998 Clean up of earlier versions.
% Revised:
%
%-----o-----o-----o-----o-----o-----o-----o-----
o

% 1 Plot frequency response of filter in figure 1:
f1=figure(1);clf % freq resp
w=logspace(-1,2,150);
[magF,phF,w] = bode(sys1,w);
nw=size(w);
magFF=reshape(magF, [nw 1]);
phFF =reshape(phF, [nw 1]);

% 2 Magnitude (top axes)
h1(1)=subplot(2,1,1);
plot(w,magFF)

set(get(h1(1),'Title'), ...
'String', 'Filter Frequency Response', ...
'FontName', 'times', ...
'FontSize', 14, ...
'FontWeight','bold')
set(h1(1), ...
'FontName', 'times', ...
'FontSize',9)

% x-axis
set(get(h1(1),'XLabel'), ...
'String', 'Frequency (rad/sec)', ...
'FontName', 'times', ...
'FontSize', 10)
set(h1(1), ...
'XScale', 'log', ...
'XLim', [.1 100], ...
'XTick', [.1 .2 .3 .4 .5 .6 .7 .8 .9 ...
1 2 3 4 5 6 7 8 9 ...
10 20 30 40 50 60 70 80 90 100], ...
'XTickLabel', ...
{.1; ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ...
1; ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ...
10; ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ' ...
100}) 

% y-axis
set(get(h1(1),'YLabel'), ...
'String', 'Amplitude', ...
'FontName', 'times', ...
'FontSize', 10)
```

```

set(h1(1), ...
'YScale', 'log', ...
'YLim', [.01 10])
grid on

% 3 Phase
h1(2)=subplot(2,1,2);
plot(w,phFF)
hold on
plot([.01 100],[0 0],'b-.')

set(h1(2), ...
'FontName','times', ...
'FontSize',9)

% x-axis
set(get(h1(2), 'XLabel'), ...
/String', 'Frequency (rad/sec)', ...
'FontName', 'times', ...
'FontSize', 10)
set(h1(2), ...
'XScale', 'log', ...
'XLim', [.1 100], ...
'XTick', [.1 .2 .3 .4 .5 .6 .7 .8 .9 ...
1 2 3 4 5 6 7 8 9 ...
10 20 30 40 50 60 70 80 90 100], ...
'XTickLabel', ...
{.1; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ...
1; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ...
10; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ; ' ' ;100})

% y-axis
set(get(h1(2), 'YLabel'), ...
/String', 'Phase (deg)', ...
'FontName', 'times', ...
'FontSize', 10)
set(h1(2), ...
'YScale', 'linear', ...
'YLim', [-200 +200])
grid on

% 2 Plot time histories of filtered and unfiltered I/O in figure 2:
f2=figure(2);clf
h2(1)=subplot(2,1,1);plot(0,0,'.'),hold on % time hist
set(h2(1), 'Xlim',[0 130], 'YLim',[-25 25], 'FontName','Times')
set(get(h2(1), 'Title'), 'String', ['Filtered and Unfiltered I/O'], ...
'FontName','times', 'FontSize',14, 'FontWeight','bold')
set(get(h2(1), 'XLabel'), 'String', 'Time (sec)', ...
'FontName','times', 'FontSize',10, 'FontWeight','normal')
set(get(h2(1), 'YLabel'), 'String', 'Smoothed I/O', ...
'FontName','times', 'FontSize',10, 'FontWeight','normal')

plot(t(:,1), qFd(:,1),'-r'),hold on, grid on
plot(t(:,1), FeFd(:,1),'-b')
plot(plotArra2(:,1),plotArra2(:,2),'b*') % Fpk up
plot(plotArra2(:,1),plotArra2(:,3),'bo')

plot(plotArra3(:,1),plotArra3(:,2),'r*') % qPk up

```

```

plot(plotArra3(:,1),plotArra3(:,3),'ro')

h2(2)=subplot(2,1,2);plot(0,0,'.'),hold on % time hist
set(h2(2), ...
'Xlim',[0 130], ...
'YLim',[-25 25], ...
'FontName','Times')
set(get(h2(2),'XLabel'), ...
'String', 'Time (sec)', ...
'FontName','times', ...
'FontSize',10, ...
'FontWeight','normal')
set(get(h2(2),'YLabel'), ...
'String', 'Unsmoothed I/O', ...
'FontName','times', ...
'FontSize',10, ...
'FontWeight','normal')

plot(t(:, q(:, '-r')),hold on, grid on
plot(t(:, Fe(:, '-b'))
plot(t(:, nz(:, '-g'))
scl=axis;
text(scl(1)+.05*(scl(2)-scl(1)),scl(3)+.95*(scl(4)-scl(3)), ...
['Run: ' filename])

% 3 Plot identified natural frequency and phase lag of I/O in figure 3:
f3=figure(3);clf

h3(1)=subplot(2,1,1);hold on, grid on % freq
plot(plotArray(:,1),plotArray(:,3), 'ok'),hold on

set(get(h3(1),'Title'), ...
'String', 'Identified Frequency and Phase', ...
'FontName', 'times', ...
'FontSize', 14, ...
'FontWeight','bold')

set(get(h3(1),'XLabel'), ...
'String', 'Time (sec)', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight','normal')

set(get(h3(1),'YLabel'), ...
'String', 'Frequency (rad/sec)', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight','normal')

set(h3(1), ...
'Xlim',[0 130], ...
'YLim',[0 8], ...
'FontName','Times')

h3(2)=subplot(2,1,2);hold on, grid on % phase
plot(plotArray(:,1),plotArray(:,2), 'ok'),hold on

set(get(h3(2),'XLabel'), ...

```

```

'String', 'Time (sec)', ...
'FontName','times', ...
'FontSize',10, ...
'FontWeight','normal')
set(get(h3(2),'YLabel'), ...
'String', 'Phase (deg)', ...
'FontName','times', ...
'FontSize',10, ...
'FontWeight','normal')
set(h3(2), ...
'Xlim',[0 130], ...
'YLim',[0 +200], ...
'FontName','Times')

% 4 Plot PIO parameters in figure 4:
f4=figure(4);clf % divergence
h4(1)=subplot(2,1,1);hold on, grid on % f
plot(plotArray(:,1),plotArray(:,8), '+k')

set(get(h4(1),'Title'), ...
'String', 'PIO Flags', ...
'FontName', 'times', ...
'FontSize', 14, ...
'FontWeight','bold')

set(get(h4(1), 'XLabel'), ...
'String', 'Time (sec)', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight','normal')

set(get(h4(1), 'YLabel'), ...
'String', 'PIOseverity', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight','normal')

set(h4(1), ...
'Xlim', [0 130], ...
'Yscale', 'linear', ...
'YLim', [0 4], ...
'FontName','Times')

h4(2)=subplot(2,1,2);hold on, grid on % q
plot(plotArray(:,1),0.25*plotArray(:, 9), '+k') % flag_omega
plot(plotArray(:,1),0.50*plotArray(:,10), 'xb') % flag_phase
plot(plotArray(:,1),0.75*plotArray(:,11), 'or') % flag_q
plot(plotArray(:,1),1.00*plotArray(:,12), '*r') % flag_stick

set(h4(2), ...
'Xlim', [0 130], ...
'Yscale', 'linear', ...
'YLim', [.1 1], ...
'YTick', [.25 .5 .75 1], ...
'YTickLabel',{'omega';'phase';'q';'stick'}, ...
'FontName','Times')

set(get(h4(2), 'XLabel'), ...

```

```

'String', ['Time (sec)'], ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')

set(get(h4(2), 'YLabel'), ...
'String', ['PIO Flags'], ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')

% 5 Plot PIO parameters in figure 5:
f5=figure(5);clf % divergence
h5(1)=subplot(2,1,1);hold on, grid on % f
plot(plotArray(:,1),plotArray(:,4), 'ok')
plot(plotArray(:,1),plotArray(:,5), '+k')

set(get(h5(1), 'Title'), ...
'String', 'Various PIO Functions', ...
'FontName', 'times', ...
'FontSize', 14, ...
'FontWeight', 'bold')

set(get(h5(1), 'XLabel'), ...
'String', 'Time (sec)', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')

set(get(h5(1), 'YLabel'), ...
'String', 'Fdiv', ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')

set(h5(1), ...
'Xlim', [0 130], ...
'Yscale', 'linear', ...
'YLim', [0 2], ...
'FontName', 'Times')

h5(2)=subplot(2,1,2);hold on, grid on % q
plot(plotArray(:,1),plotArray(:,6), 'ob')
plot(plotArray(:,1),plotArray(:,7), '+b')

set(h5(2), ...
'Xlim', [0 130], ...
'Yscale', 'linear', ...
'YLim', [0 60], ...
'FontName', 'Times')

set(get(h5(2), 'XLabel'), ...
'String', ['Time (sec)'], ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')

set(get(h5(2), 'YLabel'), ...

```

```
'String', ['Peak values'], ...
'FontName', 'times', ...
'FontSize', 10, ...
'FontWeight', 'normal')
```

## Appendix B: HAVE ROVER Flight Test Results

### Validation Data

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 43 ROVER: Off

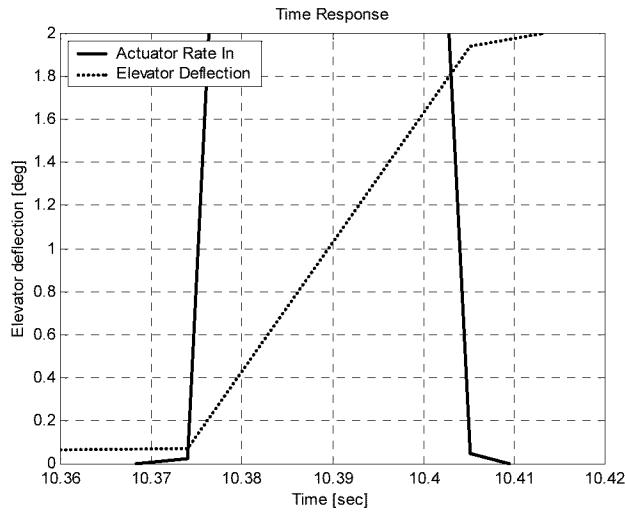


Figure B-1. Closed Loop Time Response for Configuration C (Flt 713 – 43)  
(Desired parameters – 60 deg/sec and 0 msec, Actual - 60 deg/sec, 0 msec delay)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 46 ROVER: Off

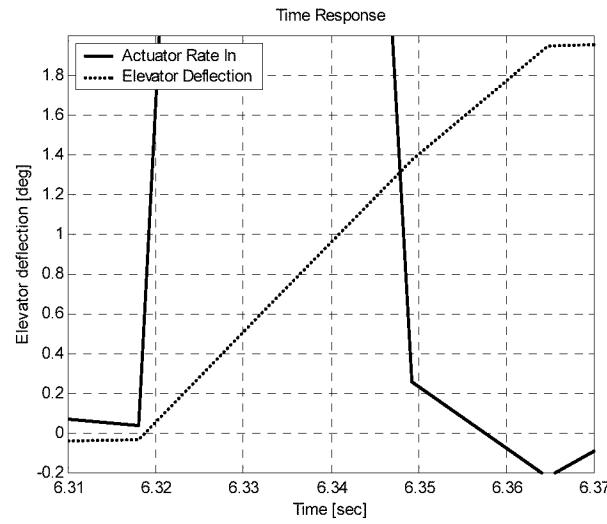


Figure B-2. Closed Loop Time Response for Configuration C (Flt 713 – 46)  
(Desired parameters – 45 deg/sec and 0 msec, Actual - 44 deg/sec, 0 msec delay)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 47 ROVER: Off

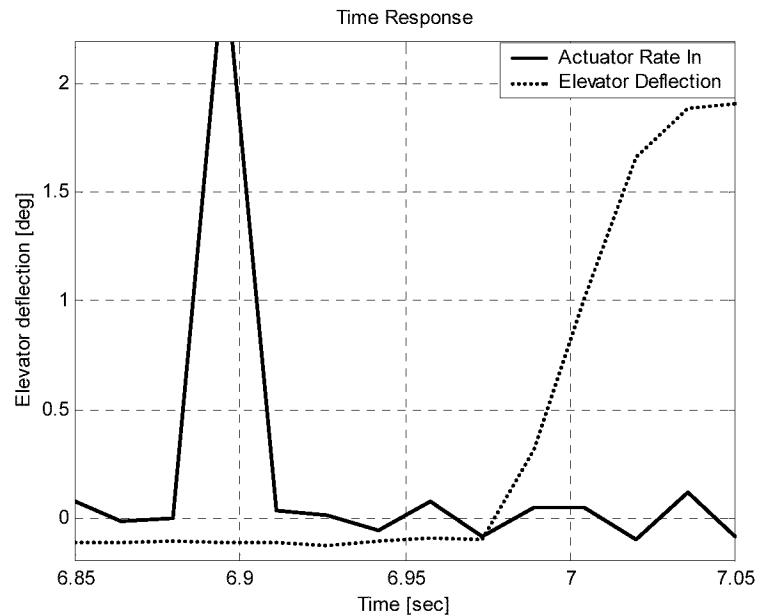


Figure B-3. Closed Loop Time Response for Configuration C (Flt 713 – 47)  
(Desired parameters – 45 deg/sec and 100 msec, Actual - 40 deg/sec, 85 msec delay)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 48 ROVER: Off

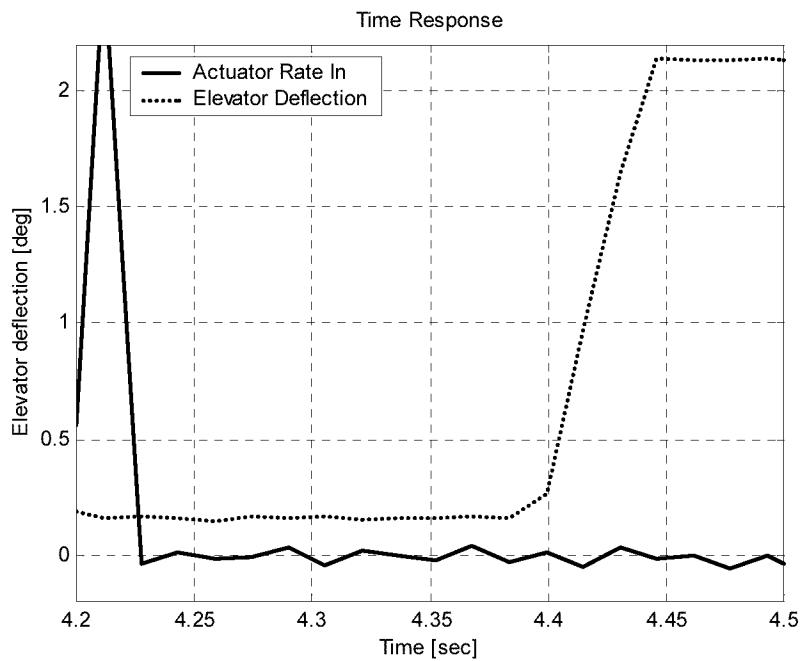


Figure B-4. Closed Loop Time Response for Configuration C (Flt 713 – 48)  
(Desired parameters – 45 deg/sec and 200 msec, Actual - 41 deg/sec, 180 msec delay)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 49 ROVER: Off

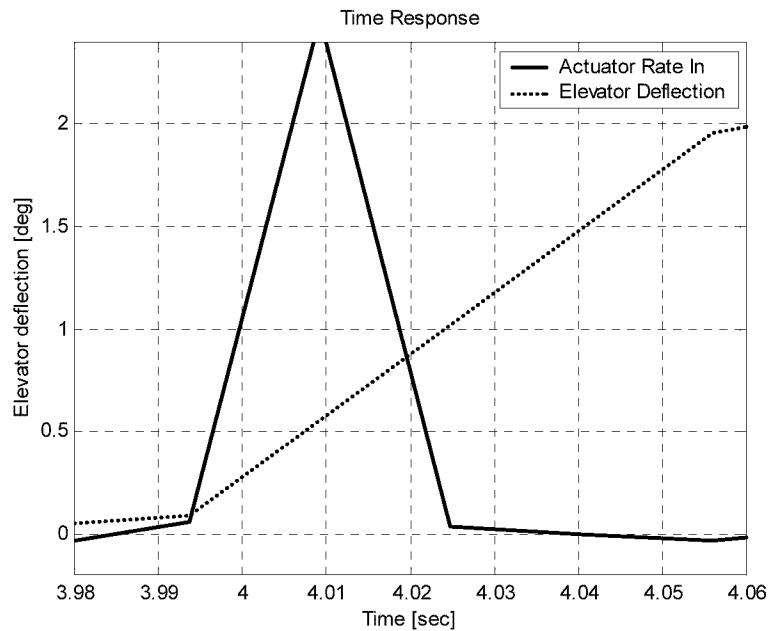


Figure B-5. Closed Loop Time Response for Configuration C (Flt 713 - 49)  
(Desired parameters – 30 deg/sec and 0 msec, Actual - 31 deg/sec, 0 msec delay)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Step Record Number: 52 ROVER: Off

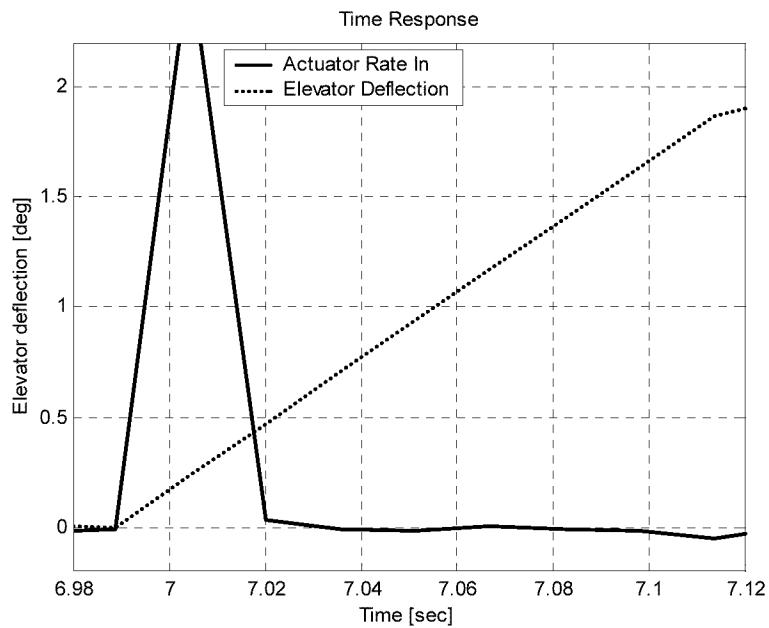


Figure B-6. Closed Loop Time Response for Configuration C (Flt 713 - 52)  
(Desired parameters – 15 deg/sec and 0 msec, Actual - 15 deg/sec, 0 msec delay)

**Test:** HAVE ROVER **Aircraft:** VISTA **Flight:** Calibration **Pilot:** Veridian  
**Maneuver:** PTI Doublet **Record Number:** 2 **ROVER:** On

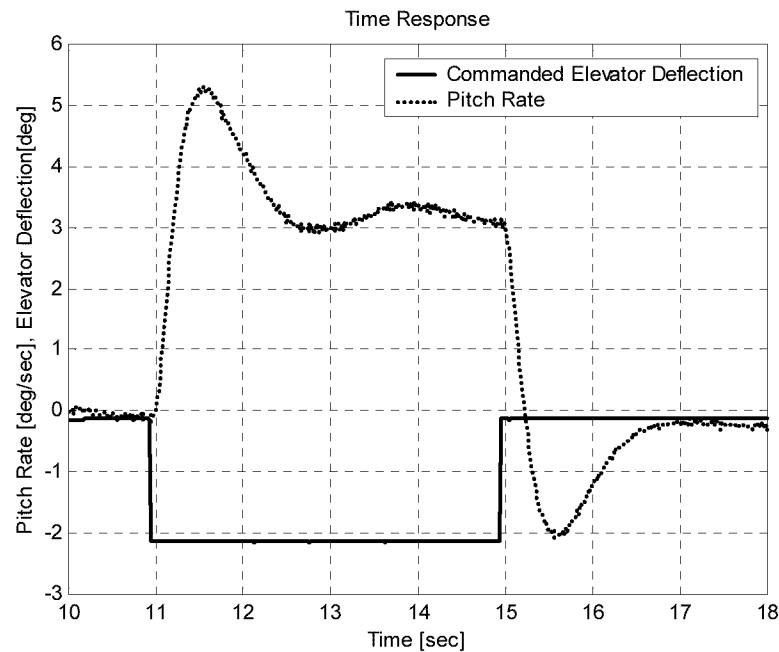


Figure B-7. Time Response for Configuration A (Flt 713 – 2, Open Loop)

**Test:** HAVE ROVER **Aircraft:** VISTA **Flight:** Calibration **Pilot:** Veridian  
**Maneuver:** PTI Doublet **Record Number:** 5 **ROVER:** Off

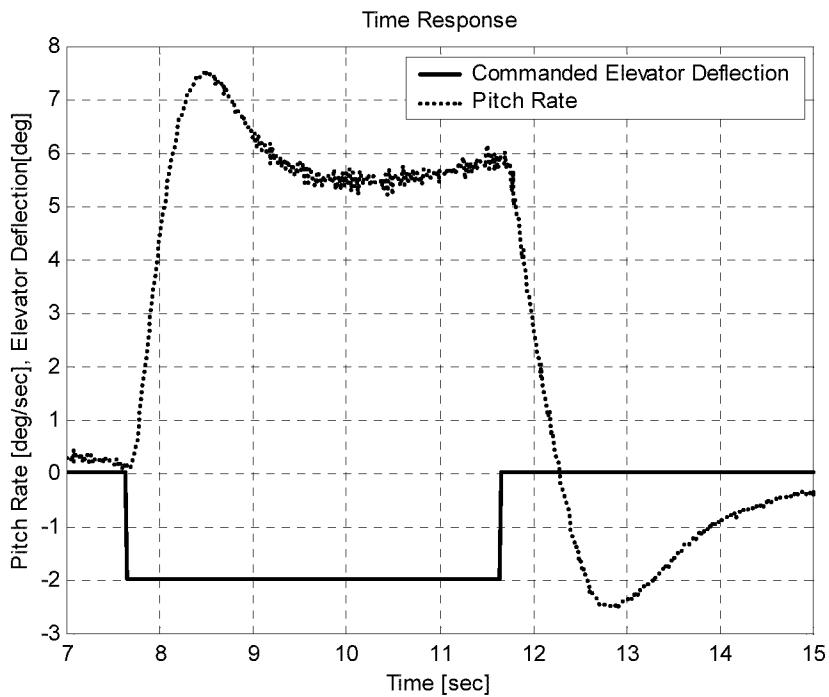


Figure B-8. Time Response for Configuration B (Flt 713 – 5, Open Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Doublet Record Number: 11 ROVER: Off

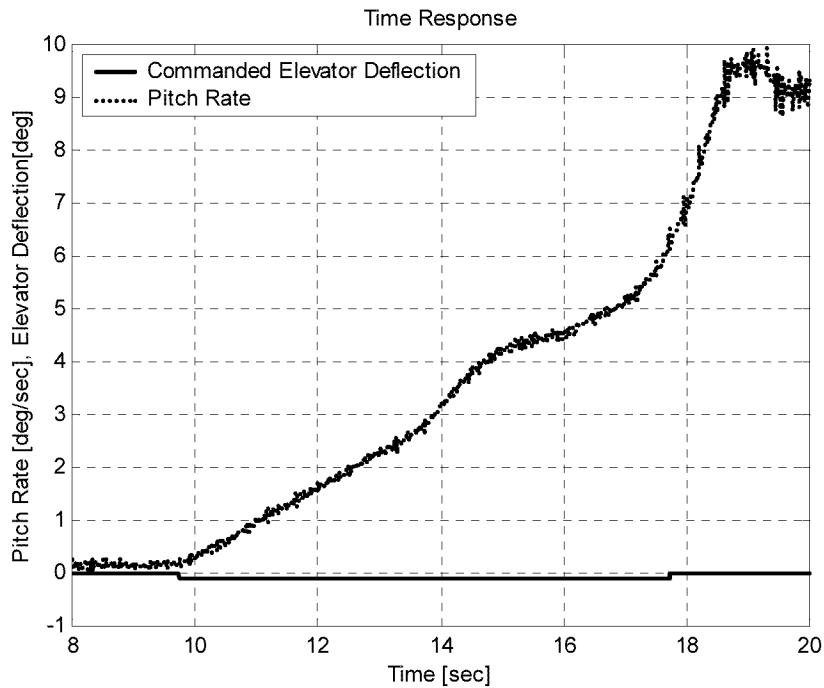


Figure B-9. Time Response for Configuration C (Flt 713 – 11, Open Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: Controls Free Record Number: 13 ROVER: Off

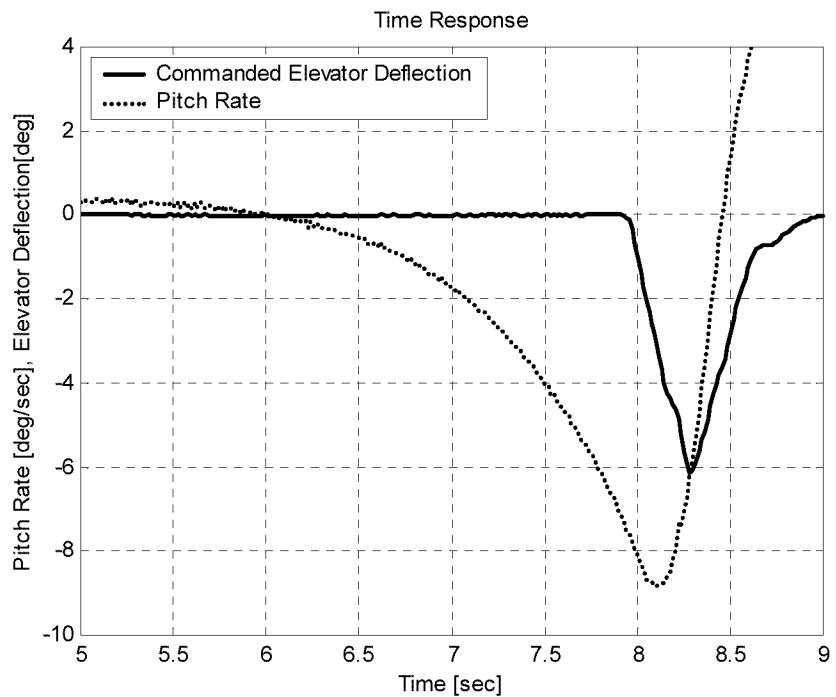


Figure B-10. Time Response for Configuration D (Flt 713 – 13, Open Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Doublet Record Number: 16 ROVER: Off

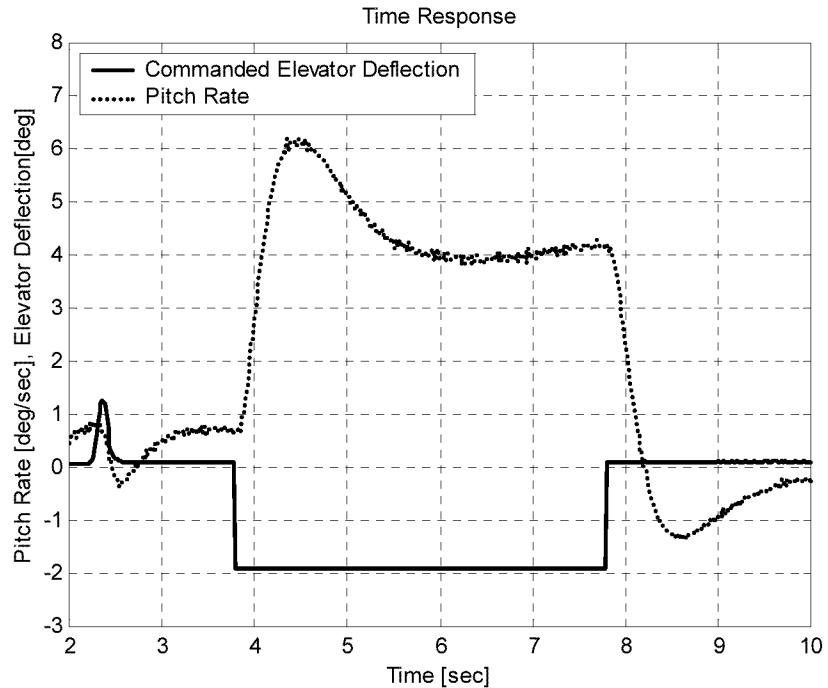


Figure B-11. Time Response for Configuration A (Flt 713 – 16, Closed Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Doublet Record Number: 19 ROVER: Off

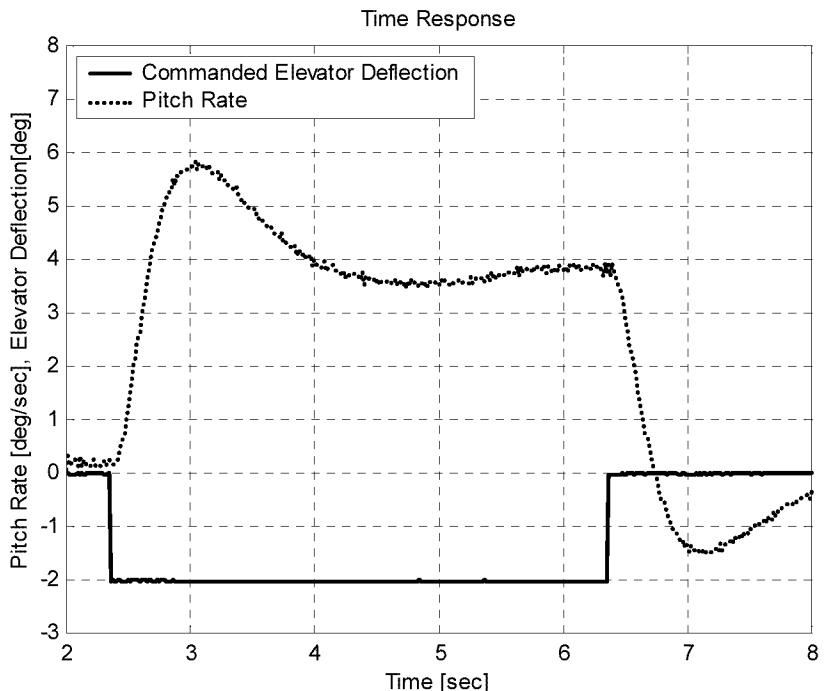


Figure B-12. Time Response for Configuration B (Flt 713 – 19, Closed Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Doublet Record Number: 22 ROVER: Off

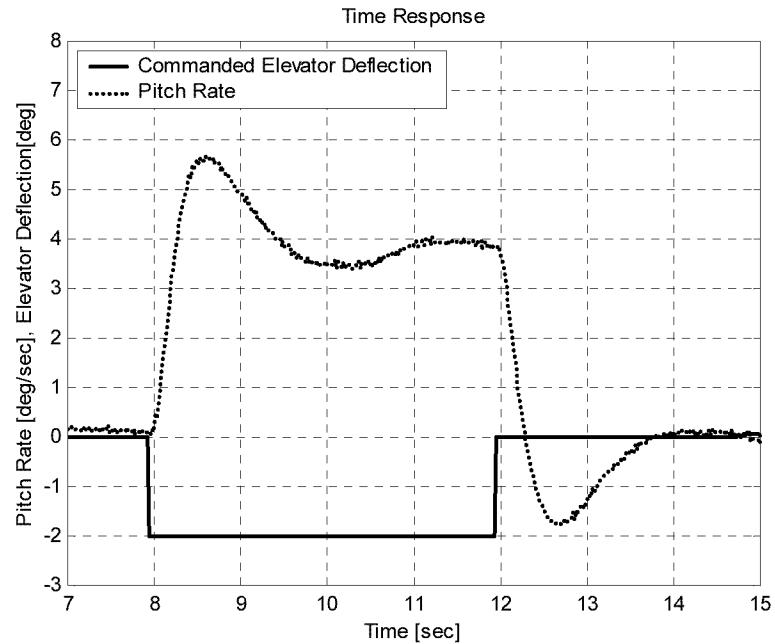


Figure B-13. Time Response for Configuration C (Flt 713 – 22, Closed Loop)

Test: HAVE ROVER Aircraft: VISTA Flight: Calibration Pilot: Veridian  
Maneuver: PTI Doublet Record Number: 25 ROVER: Off

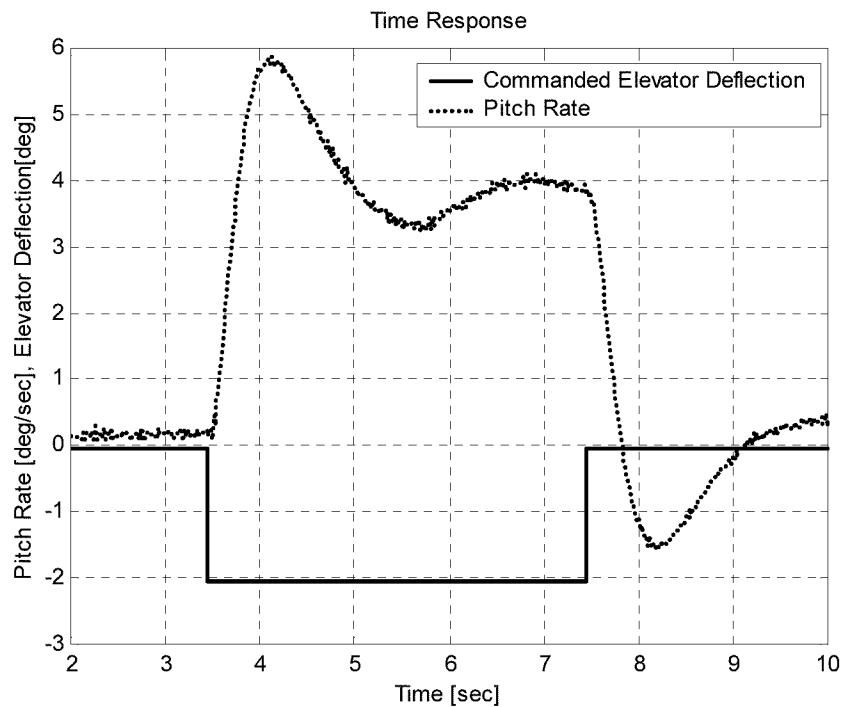


Figure B-14. Time Response for Configuration D (Flt 713 – 25, Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 3, VSS Config 517

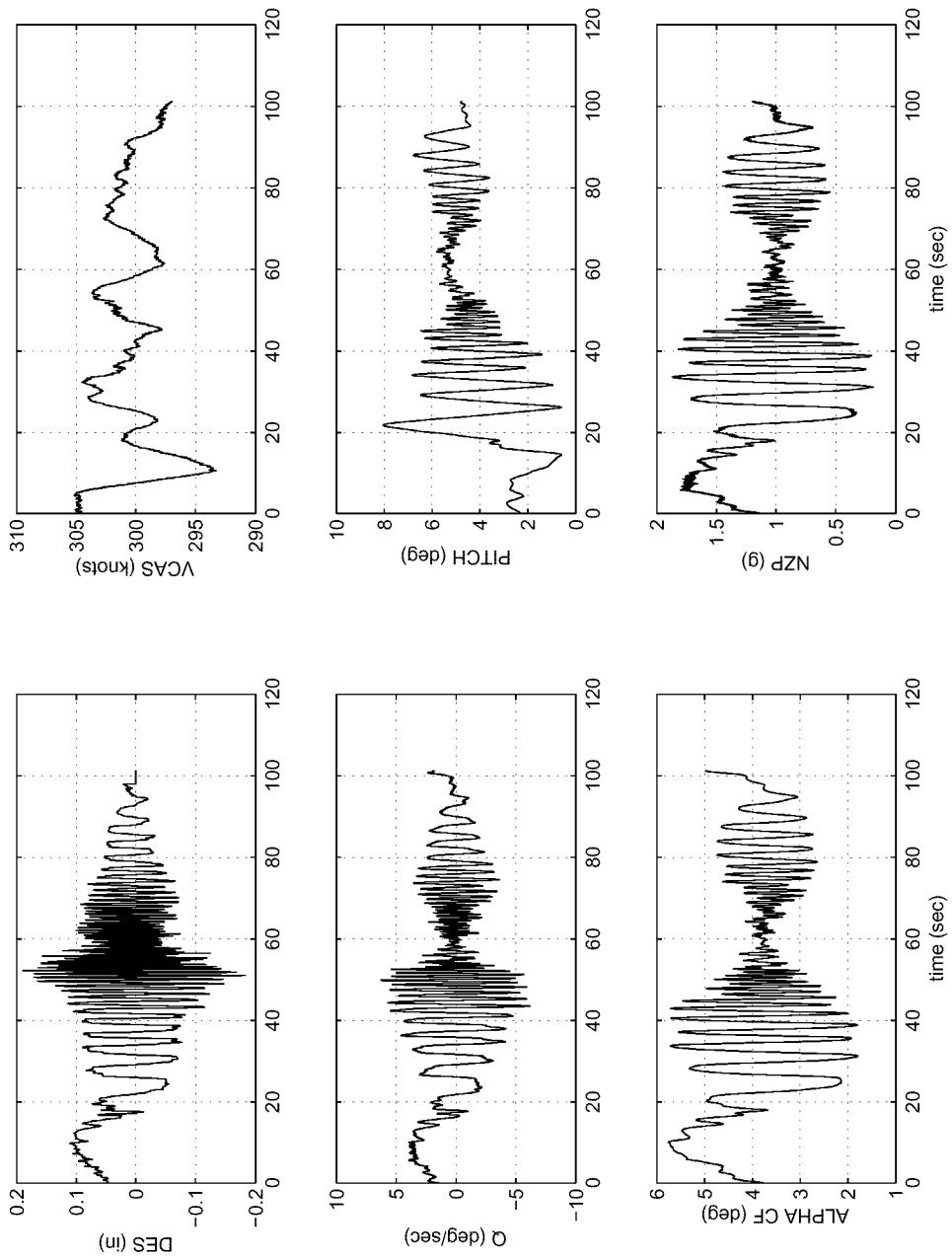


Figure B-15. Frequency Sweep for Configuration A (Open Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 3, VSS Config 517

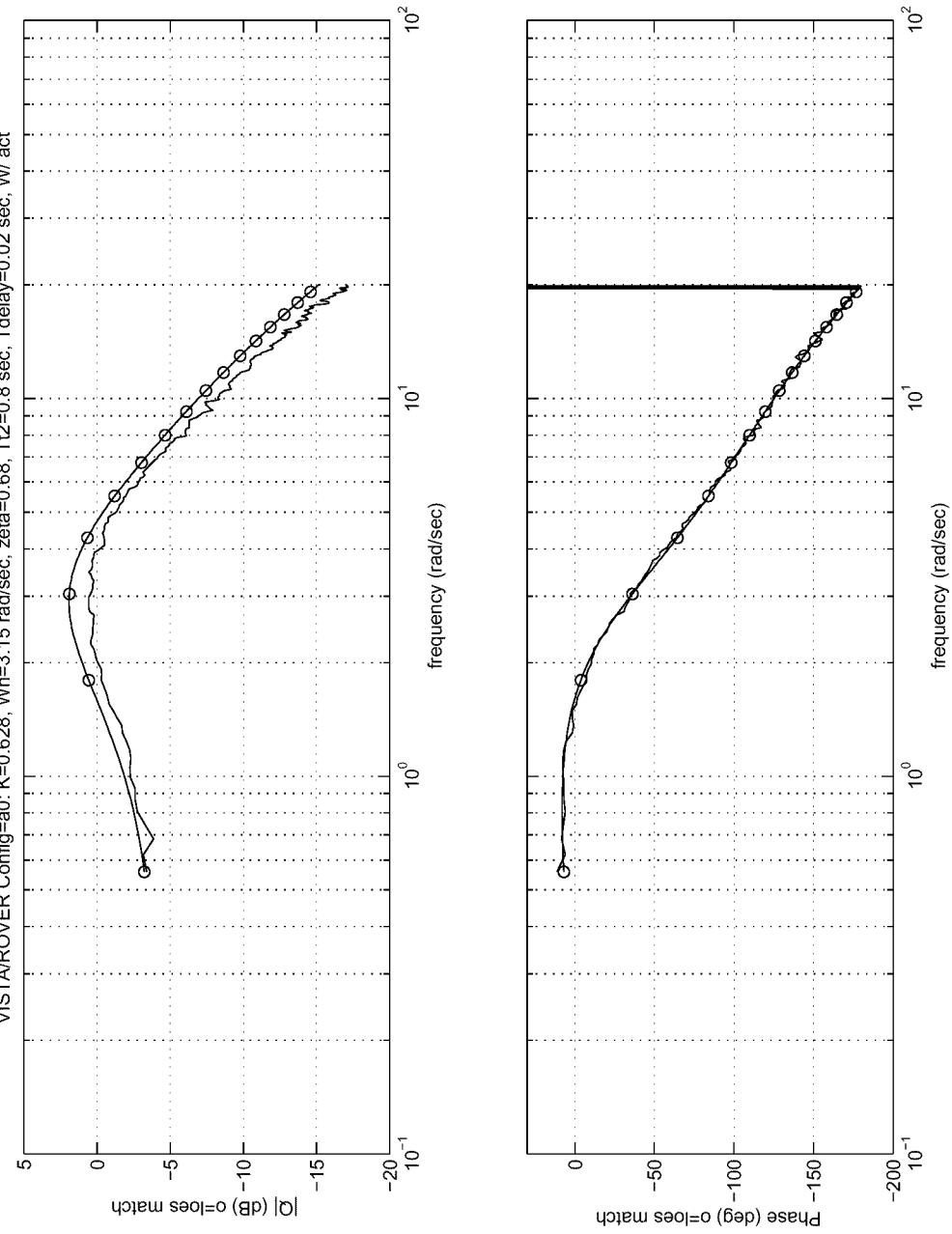


Figure B-16. Bode Plot for Configuration A (Open Loop)

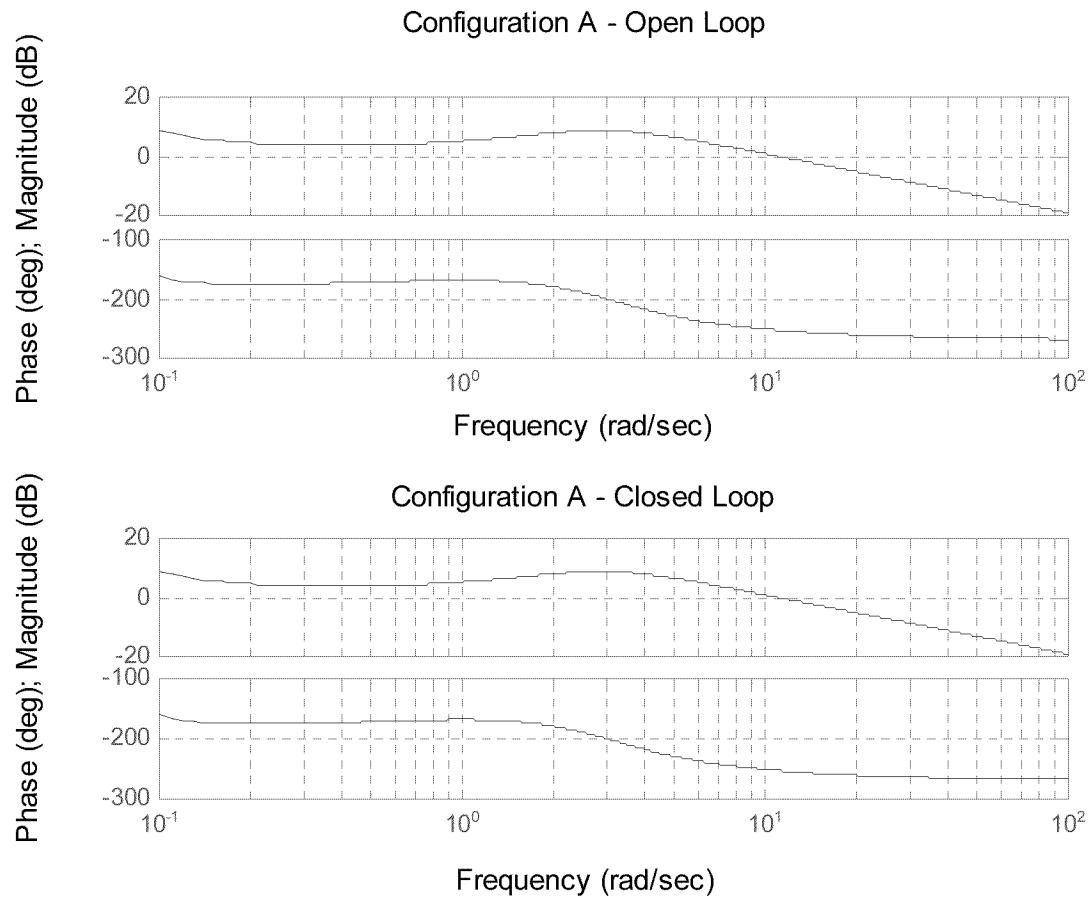


Figure B-17. Bode Plot for Simulink® Configuration A (Open & Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 6, VSS Config 526

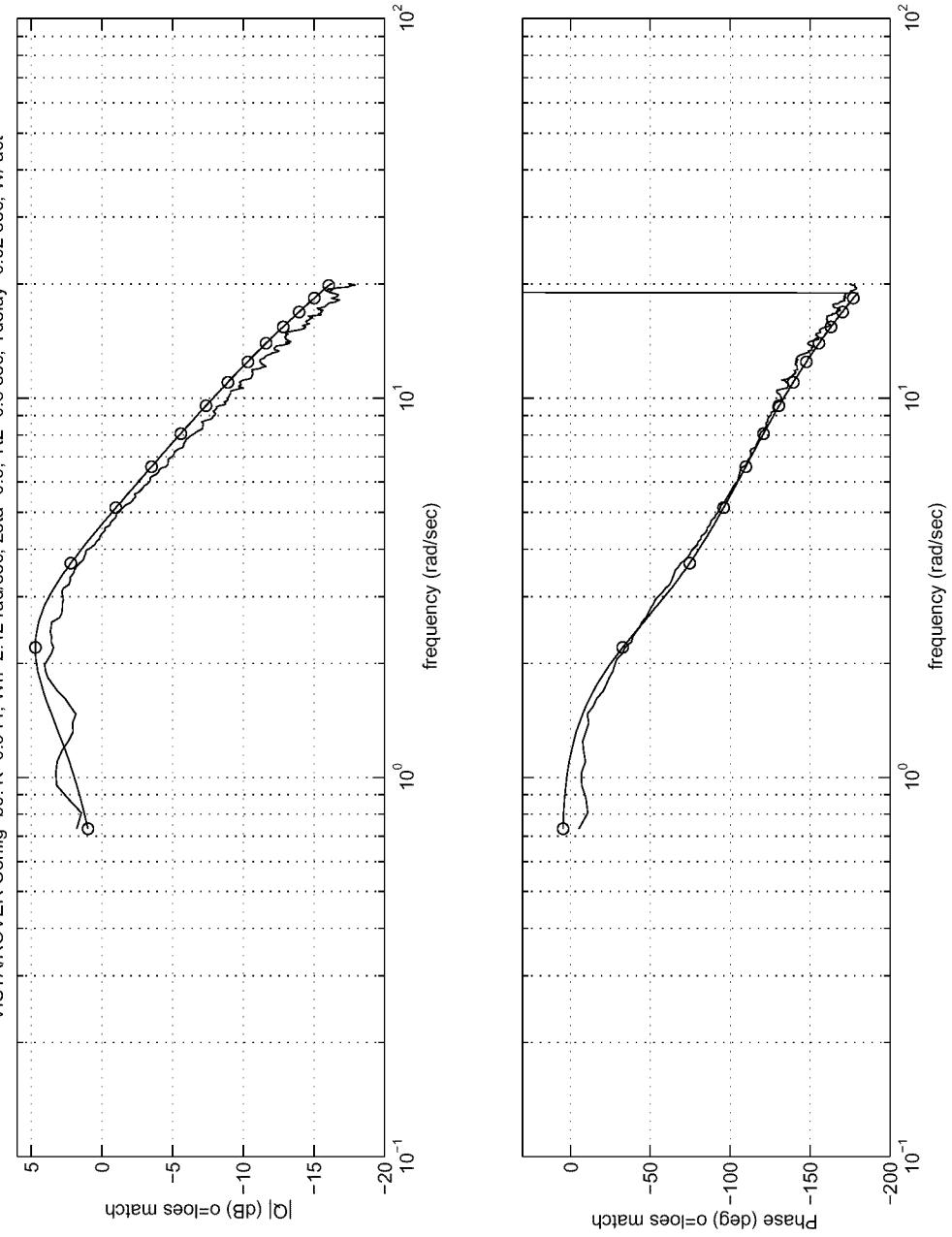


Figure B-18. Bode Plot for Configuration B (Open Loop)

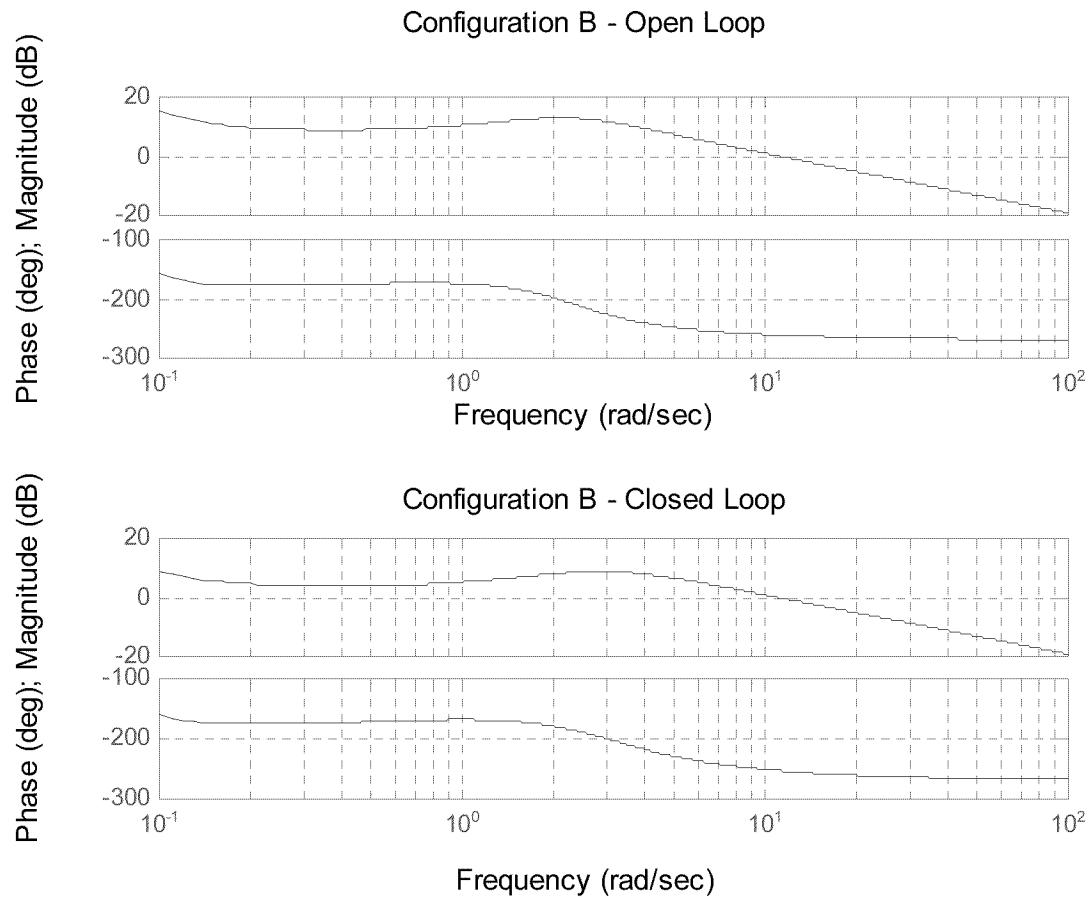


Figure B-19. Bode Plot for Simulink® Configuration B (Open & Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 12, VSS Config 536

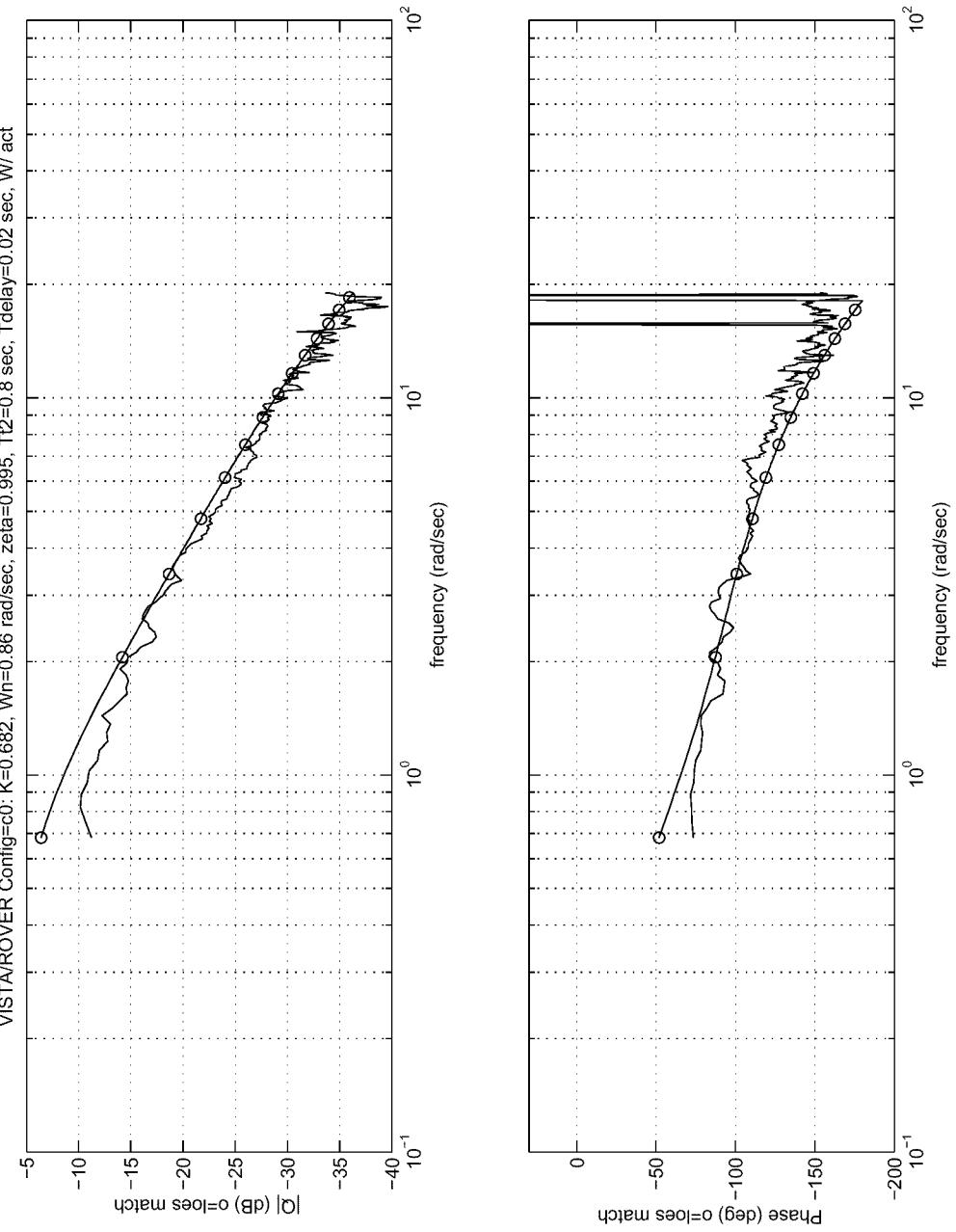


Figure B-20. Bode Plot for Configuration C (Open Loop)

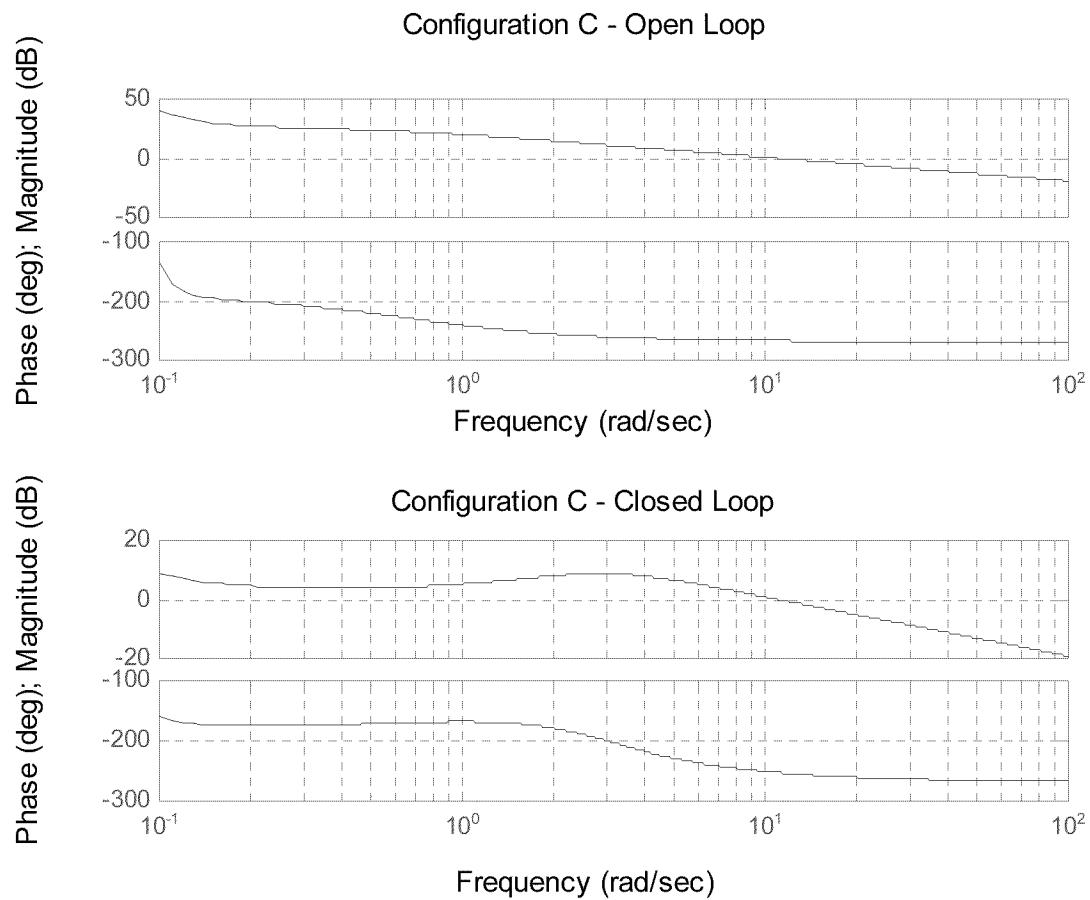


Figure B-21. Bode Plot for Simulink® Configuration C (Open & Closed Loop)

VISTA HAVE ROVER Flight 716 Data, Rec 25, VSS Config 544

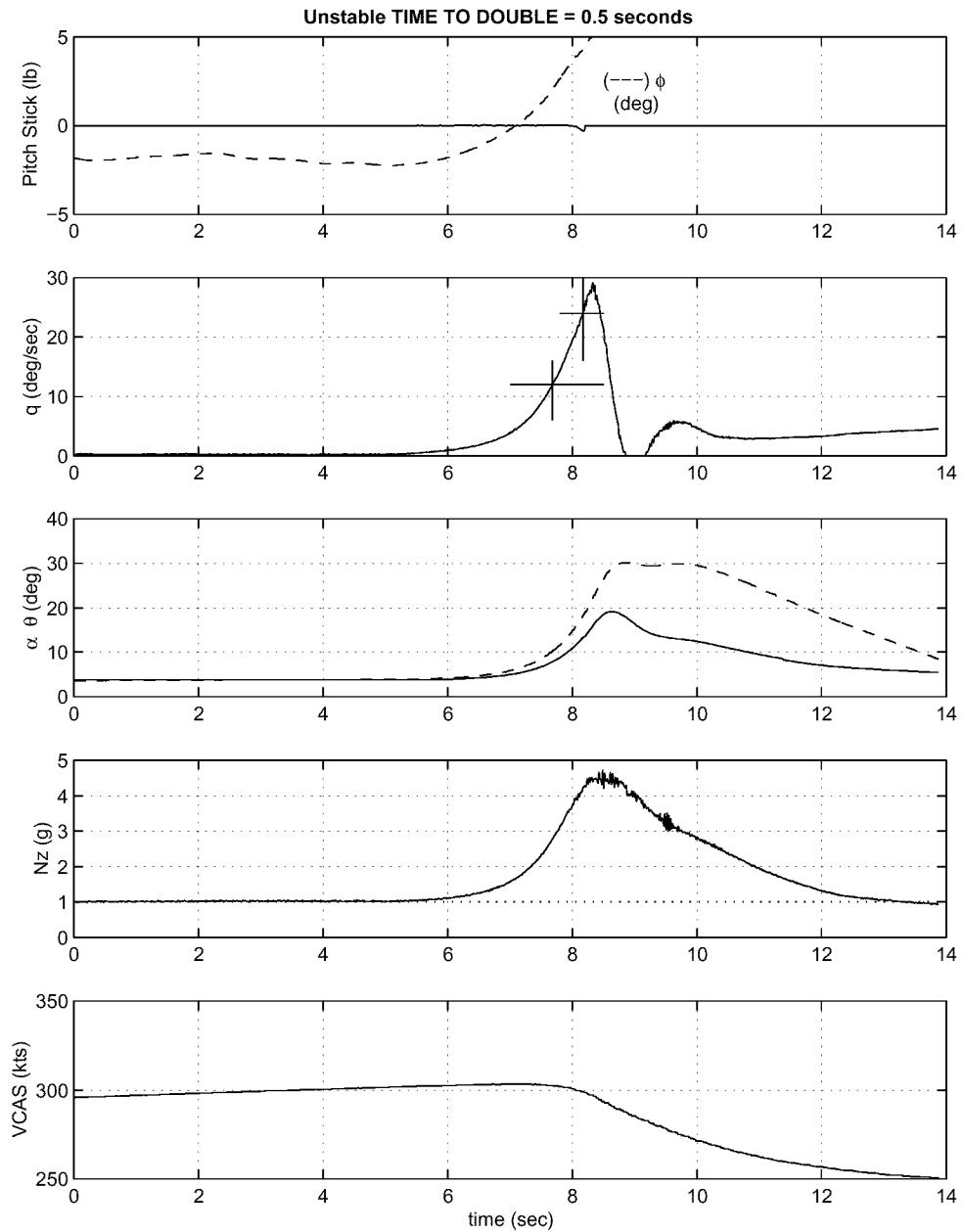


Figure B-22. Hands-off Response for Configuration D (Open Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 14, VSS Config 545

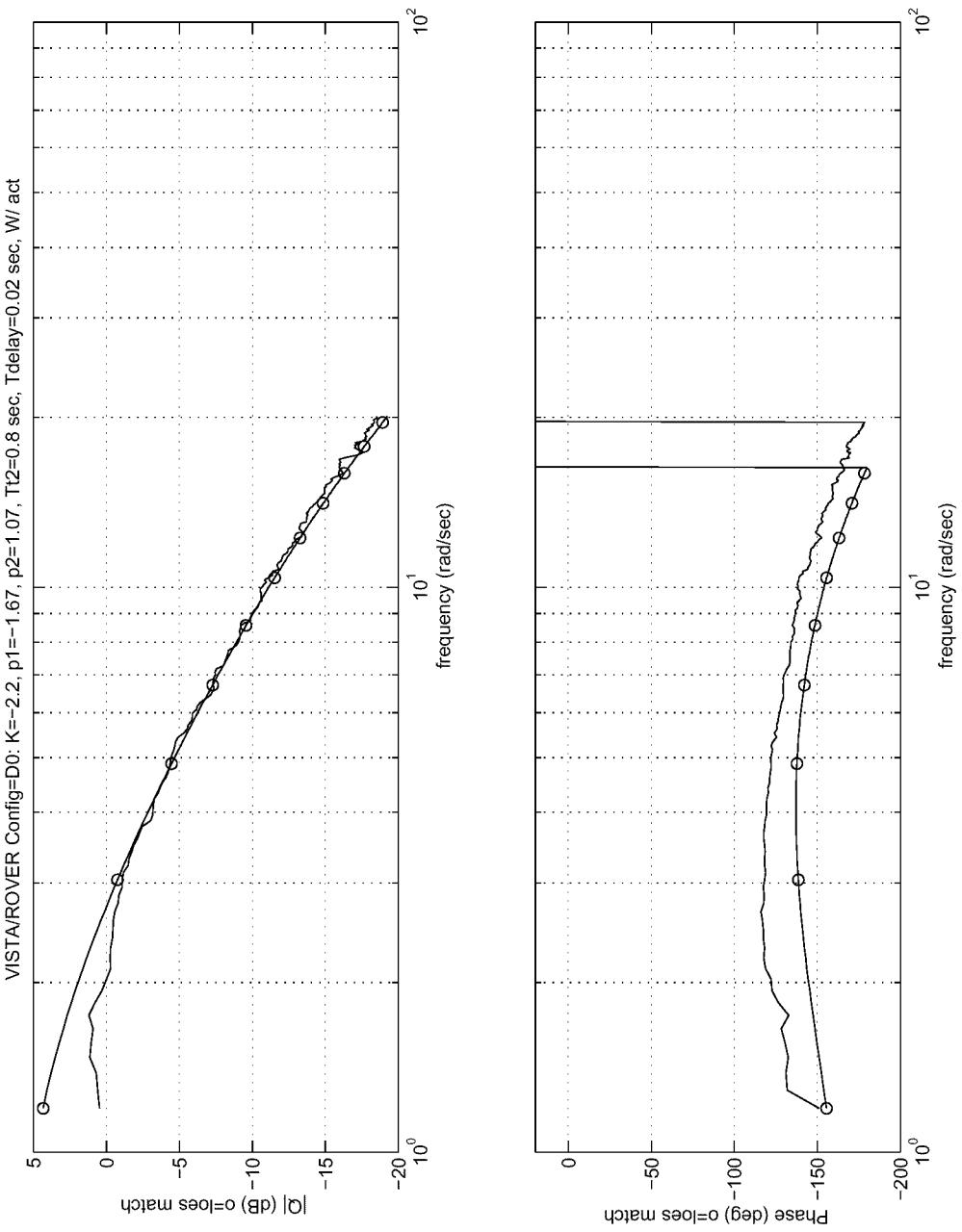


Figure B-23. Bode Plot for Configuration D (Open Loop)

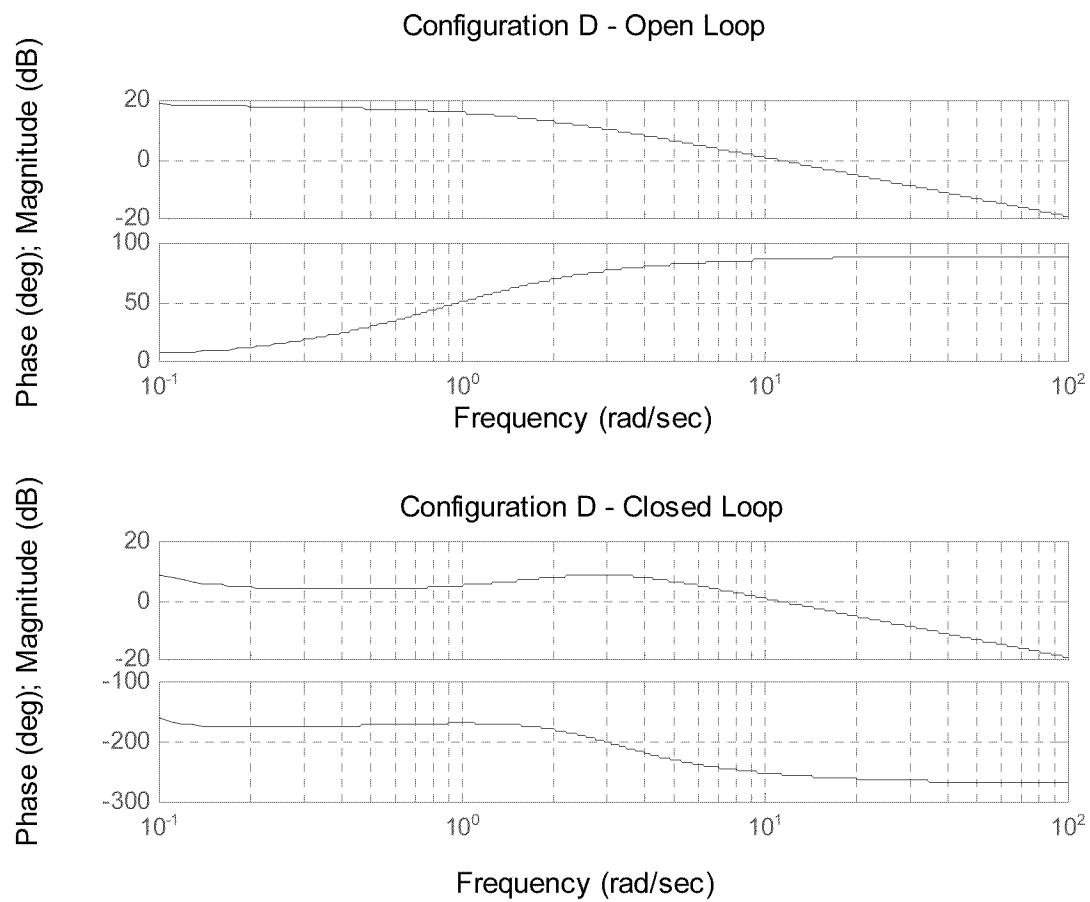


Figure B-24. Bode Plot for Simulink<sup>®</sup> Configuration D (Open & Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 17, VSS Config 555

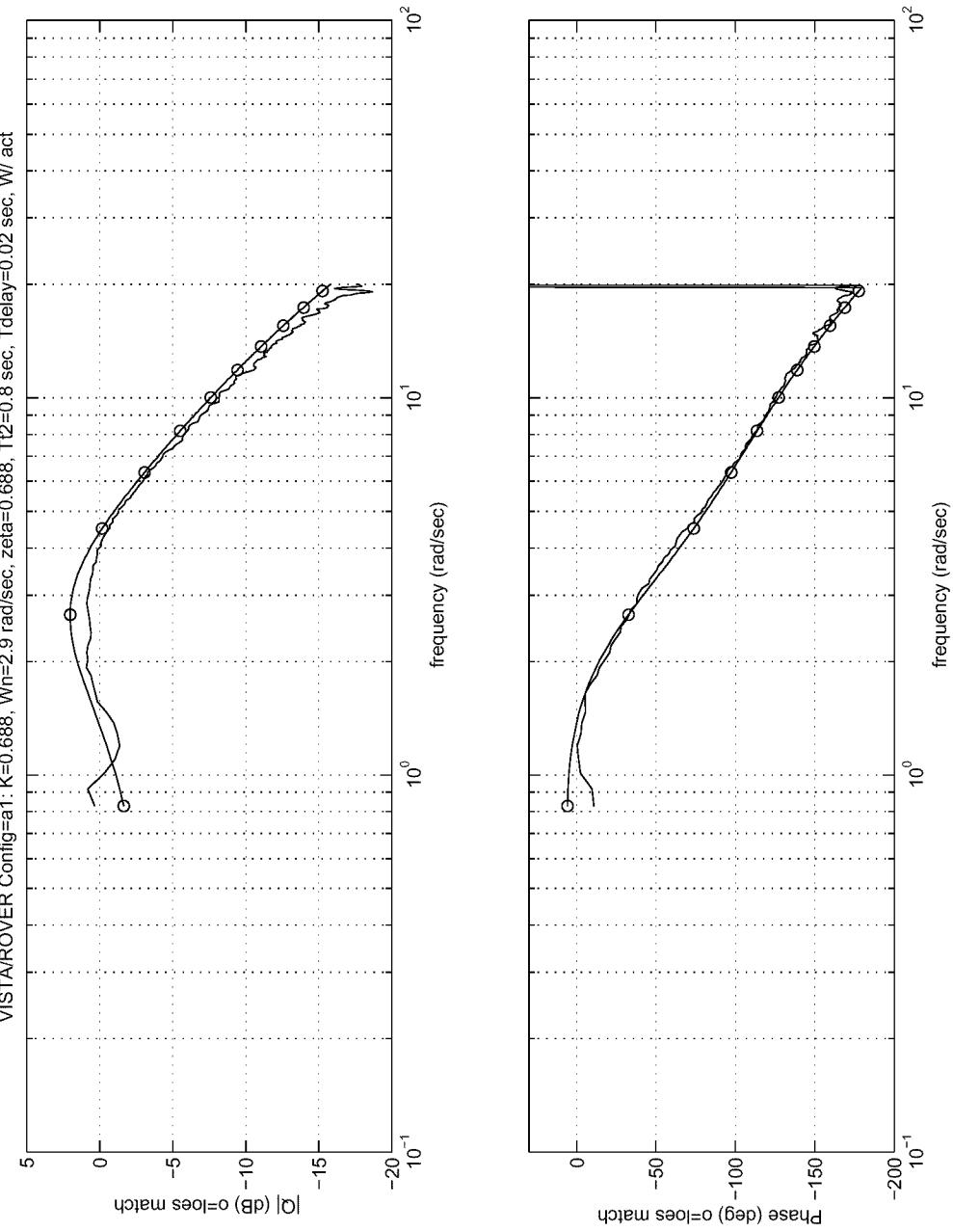


Figure B-25. Bode Plot for Configuration A (Closed Loop)

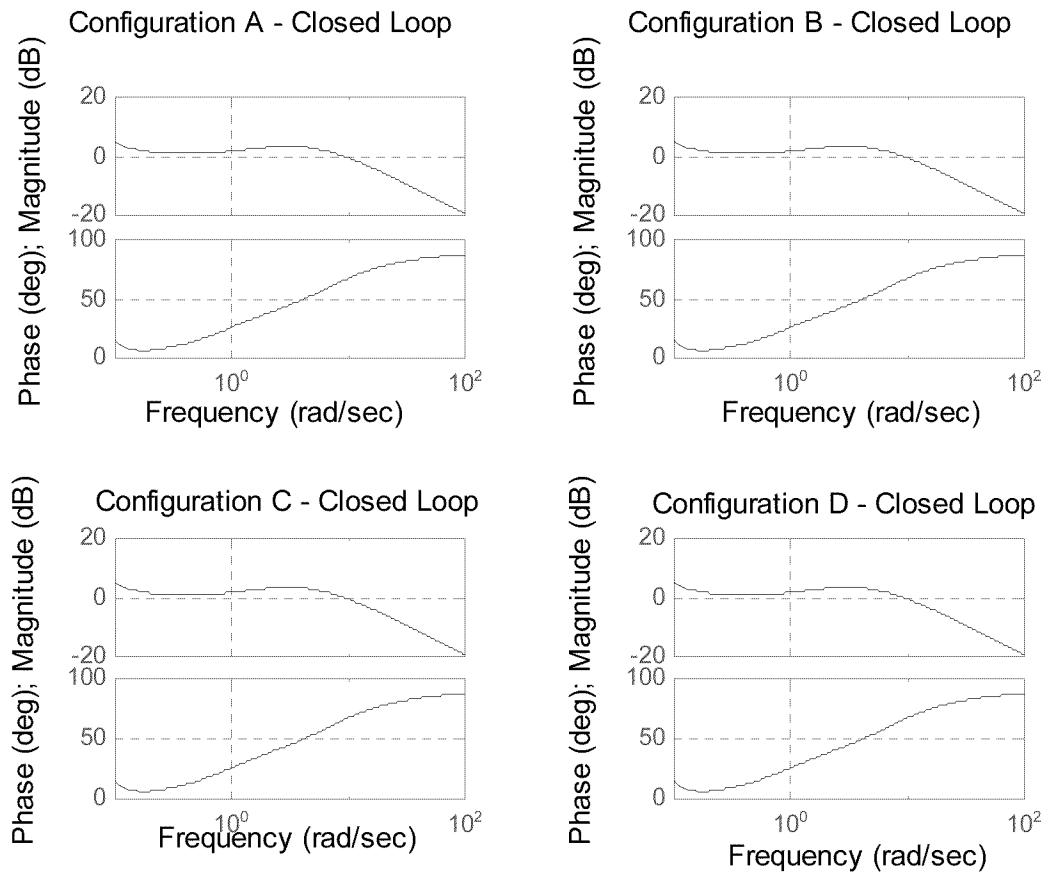


Figure B-26. Bode Plot for Simulink® Configurations A-D (Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 20, VSS Config 565

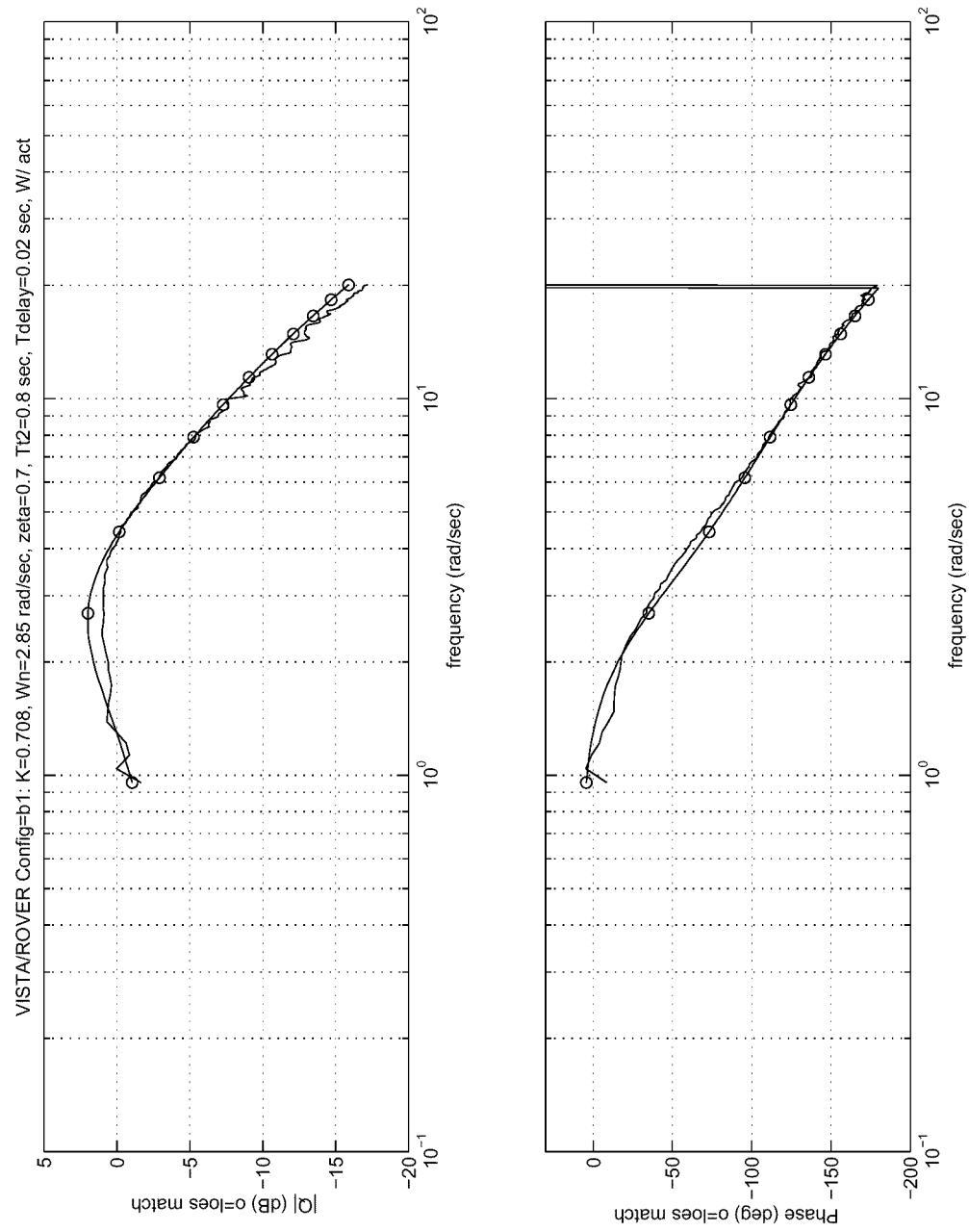


Figure B-27. Bode Plot for Configuration B (Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 23, VSS Config 575

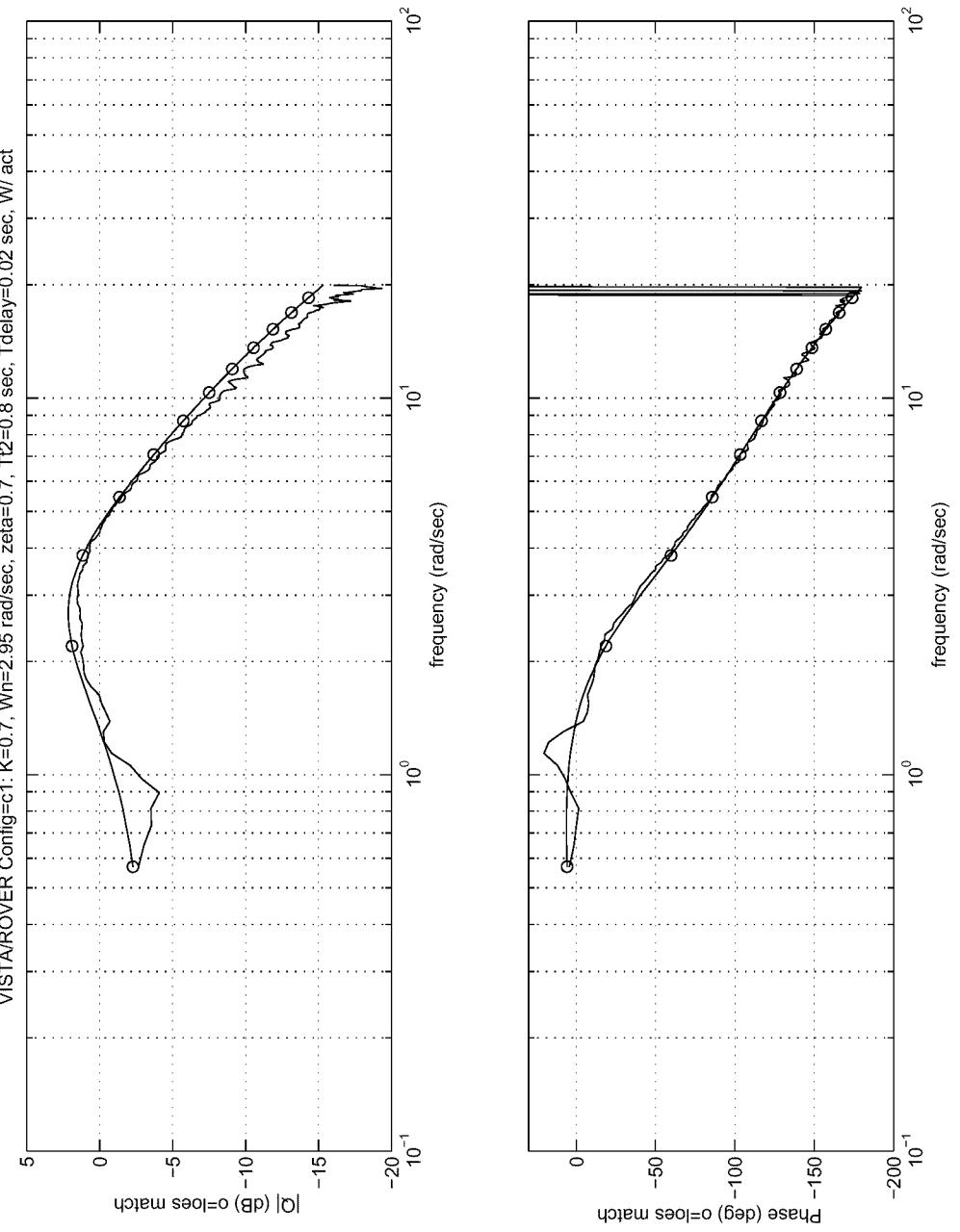


Figure B-28. Bode Plot for Configuration C (Closed Loop)

VISTA HAVE ROVER Cal Flight 1 Data, Rec 26, VSS Config 585

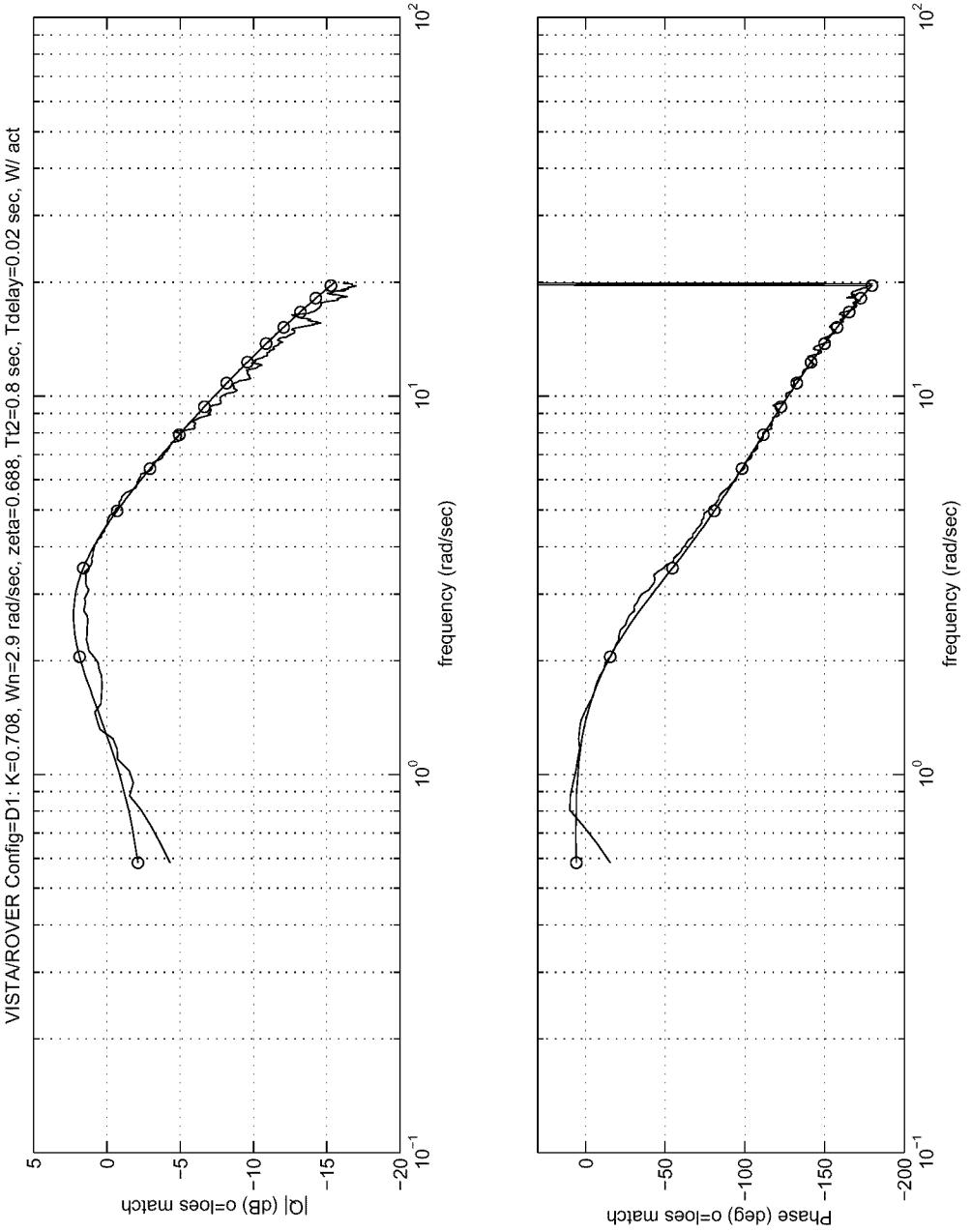


Figure B-29. Bode Plot for Configuration D (Closed Loop)

## Evaluation Data

Test: HAVE ROVER Aircraft: VISTA Flights: 1, 3 Pilots: 1,2  
Maneuver: Phase 2 HUD Record Numbers: 9, 5 ROVER: Off

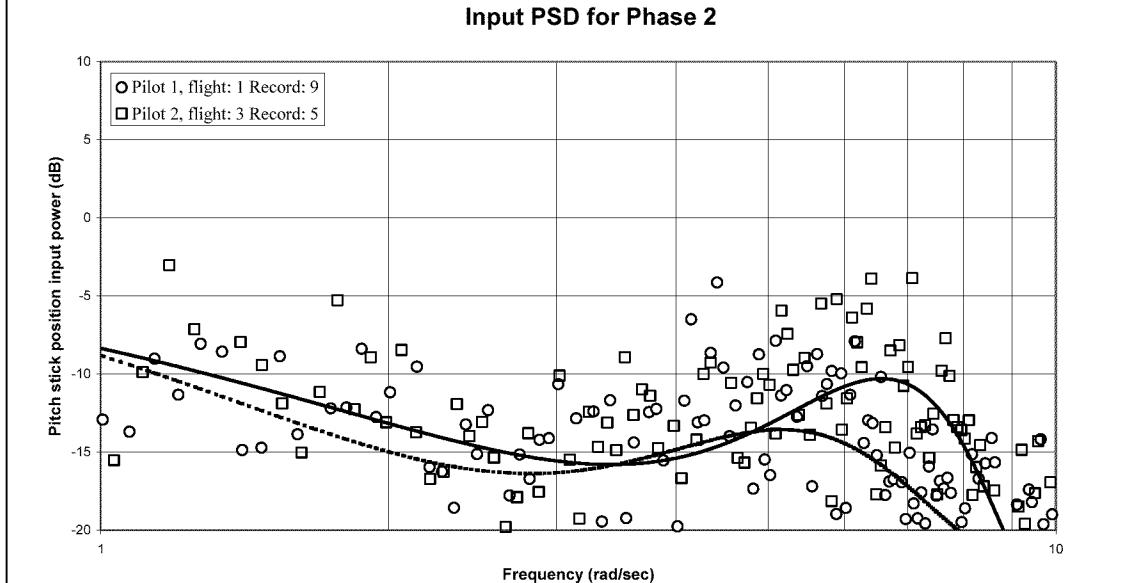


Figure B-30. Input power spectral density in phase 2 for pilots 1 and 2  
 (Configuration C, Rate limit 45 deg/sec, Time delay 0 msec)

Test: HAVE ROVER Aircraft: VISTA Flights: 2, 4 Pilot: 2,3  
Maneuver: Phase 2 HUD Record Number: 18, 1 ROVER: Off

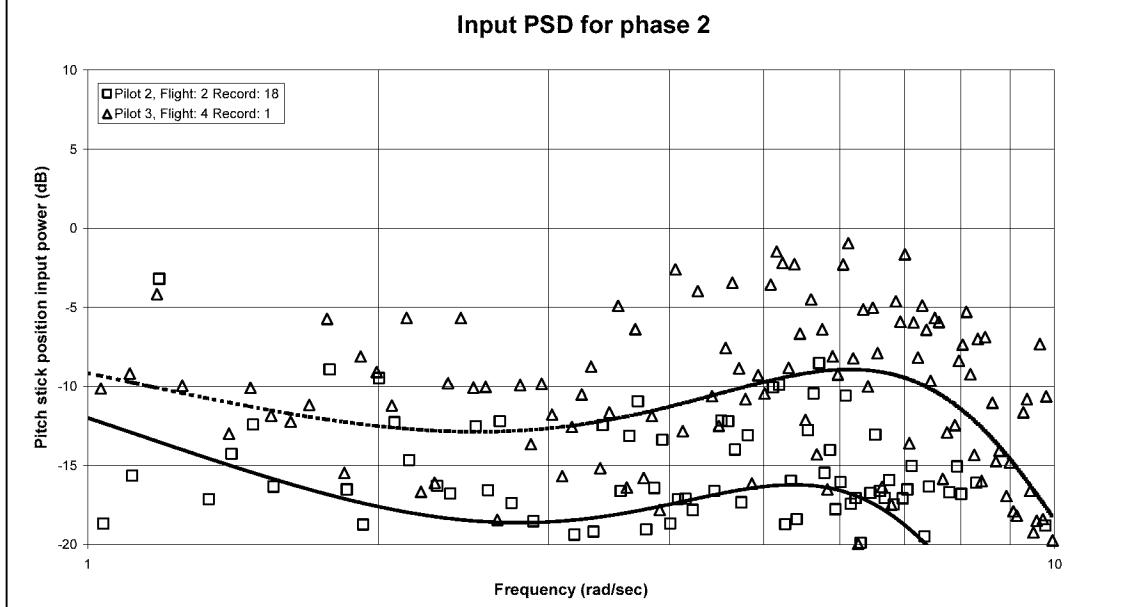


Figure B-31. Input power spectral density in phase 2 for pilots 2 and 3  
 (Configuration C, Rate limit 60 deg/sec, Time delay 0 msec)

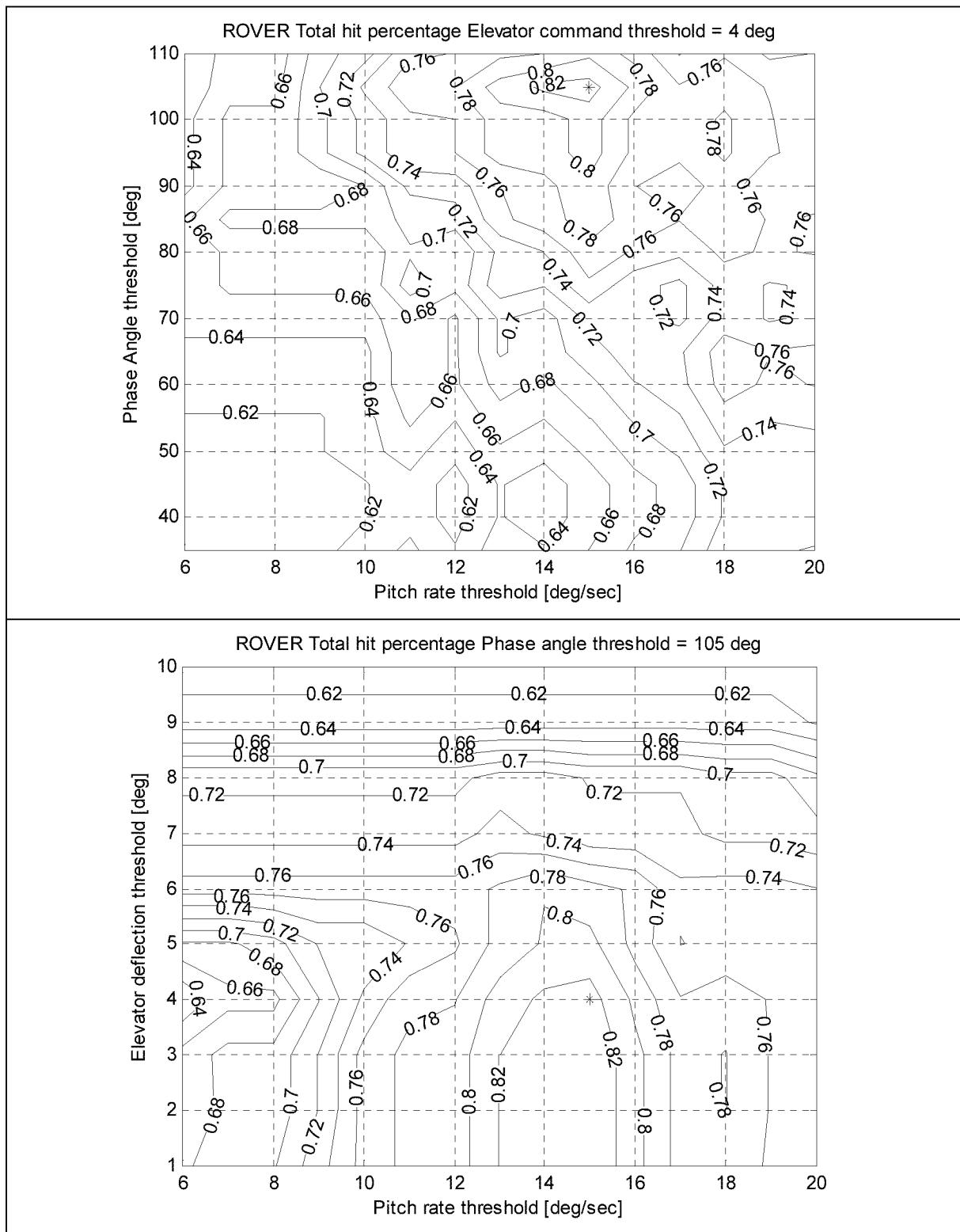


Figure B-32. Threshold Parameter Study – ROVER Total Hits  
(Contours of overall correct ROVER detections in percent)

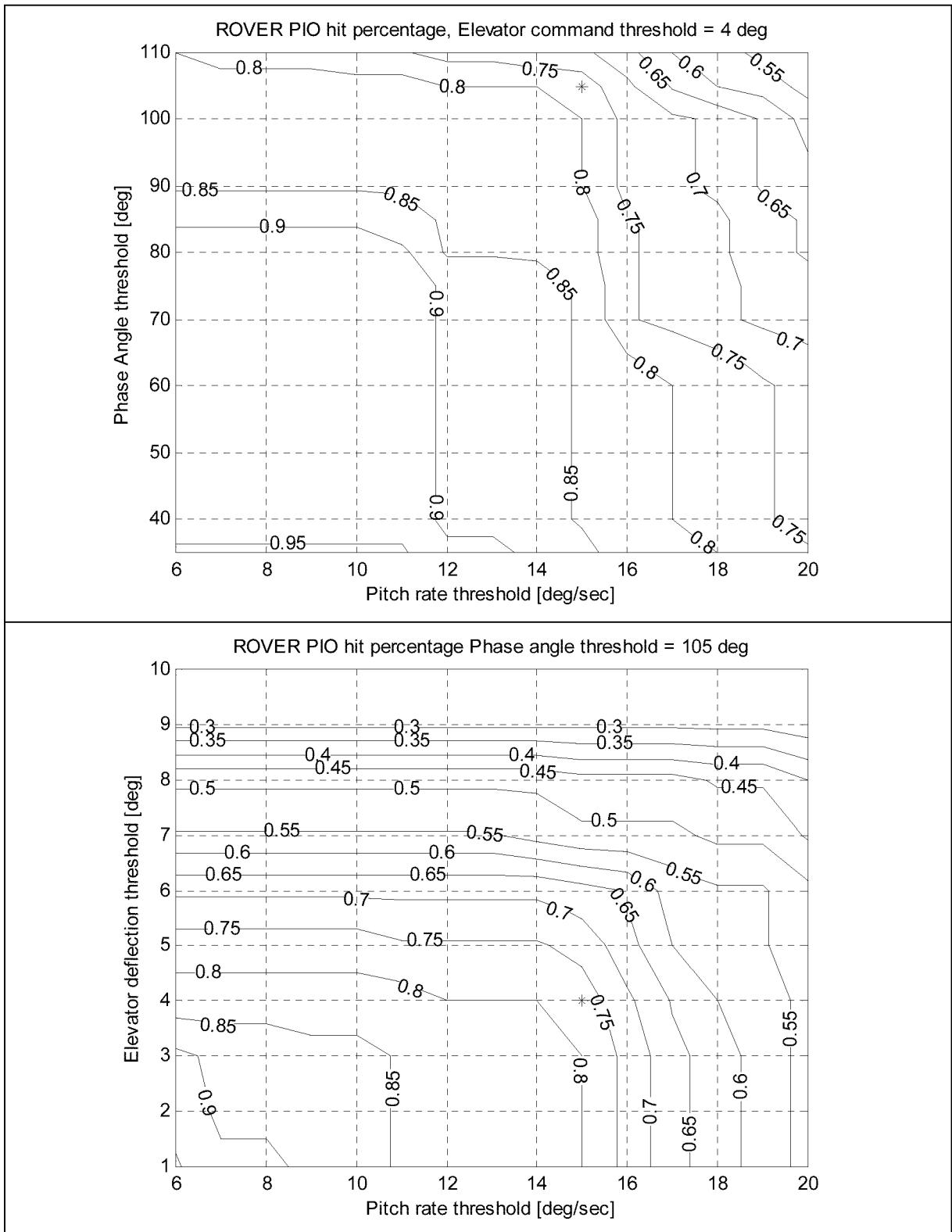


Figure B-33. Threshold Parameter Study – ROVER PIO Hits  
(Contours of correct ROVER PIO detections in percent)

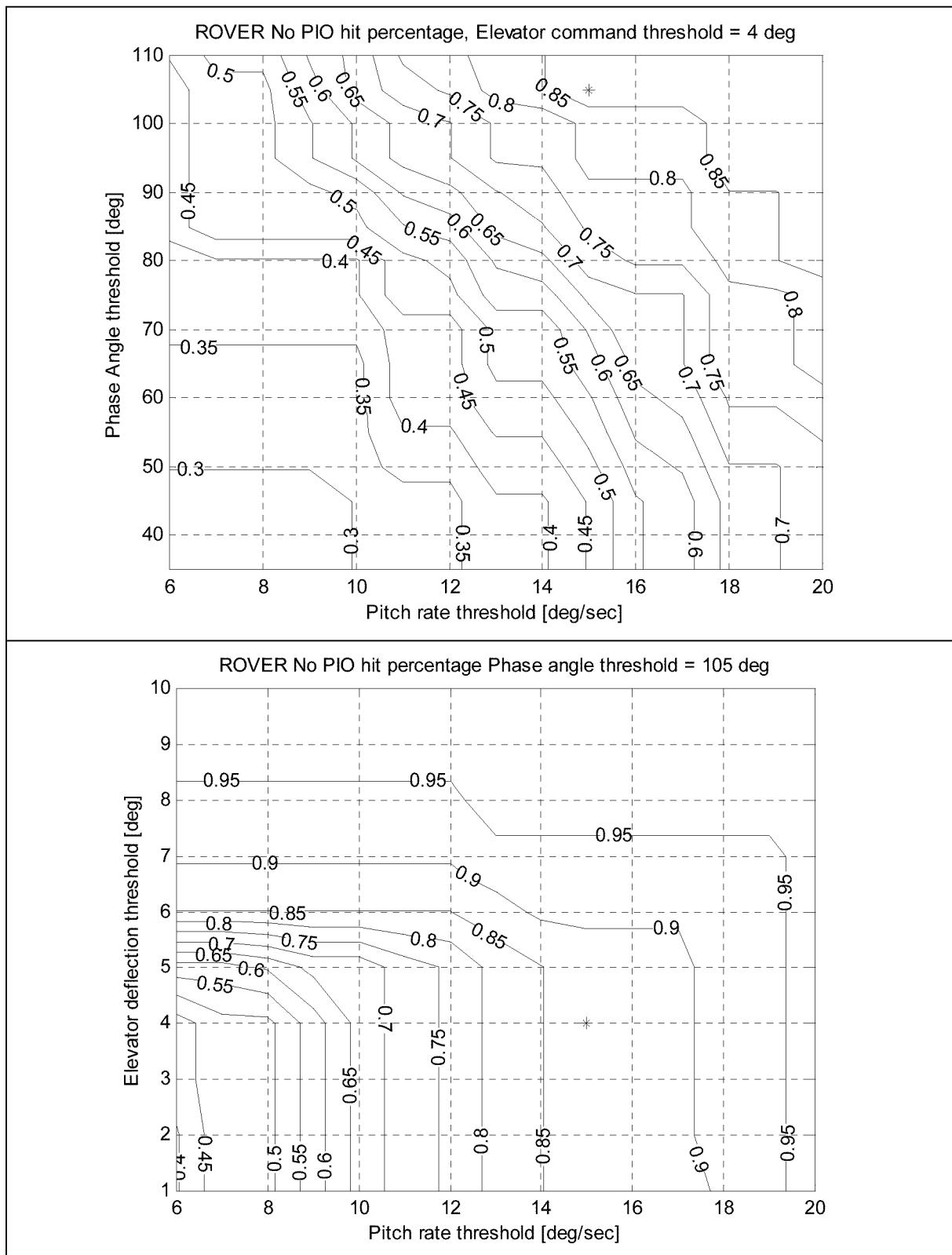


Figure B-34. Threshold Parameter Study – ROVER No PIO Hits  
(Contours of correct ROVER PIO non-detections in percent)

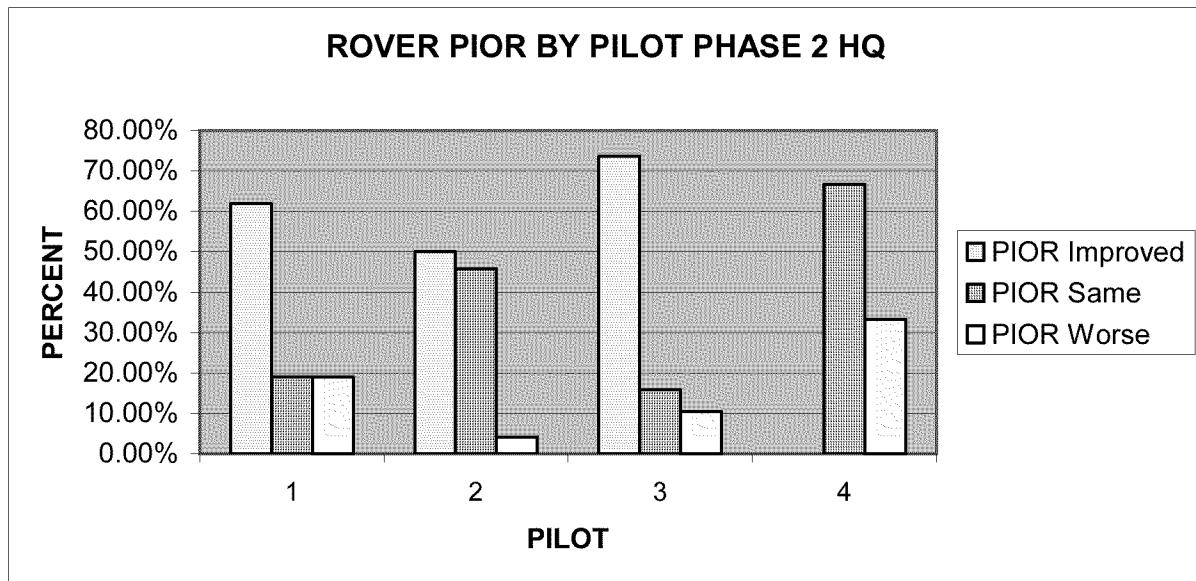


Figure B-35. PIOR Comparison – Pilot, HQ 2

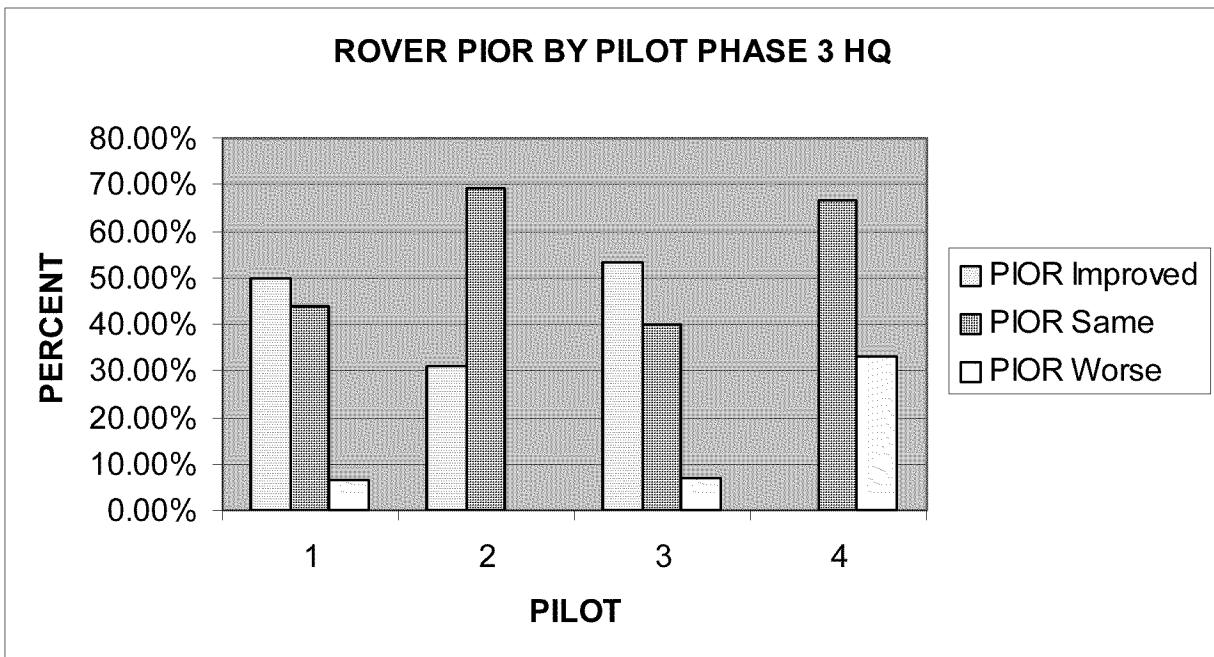


Figure B-36. PIOR Comparison – Pilot, HQ 3

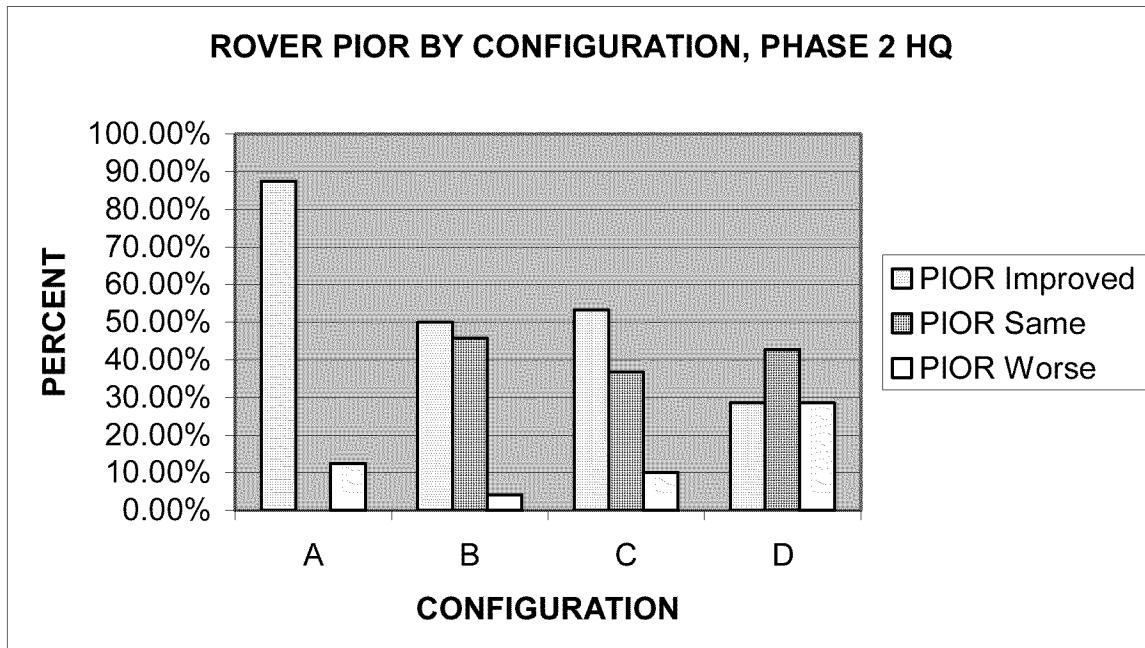


Figure B-37. PIOR Comparison – Configuration, HQ 2

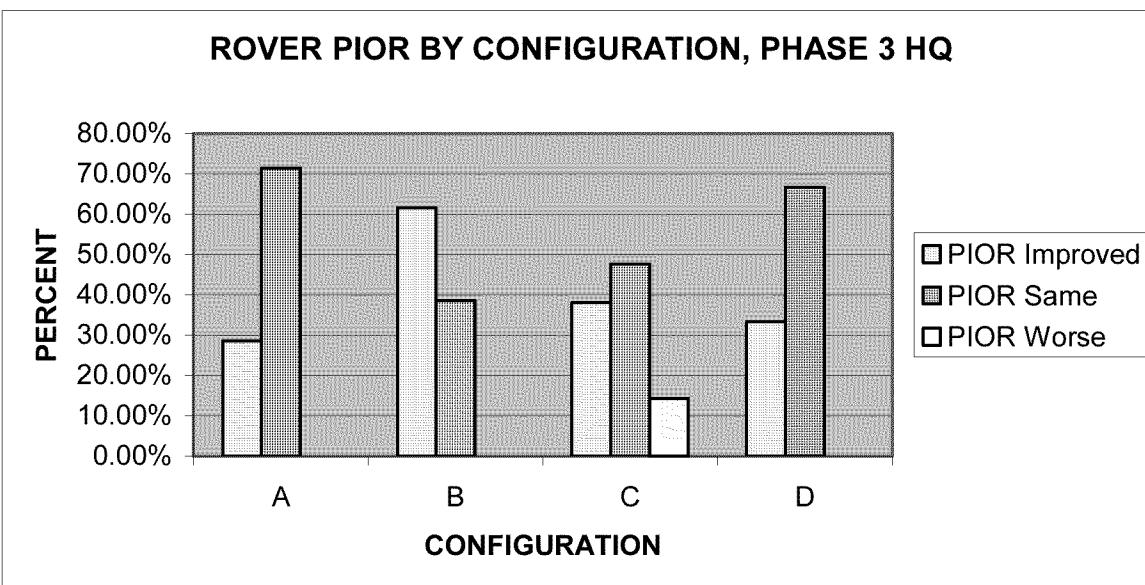


Figure B-38. PIOR Comparison – Configuration, HQ 3

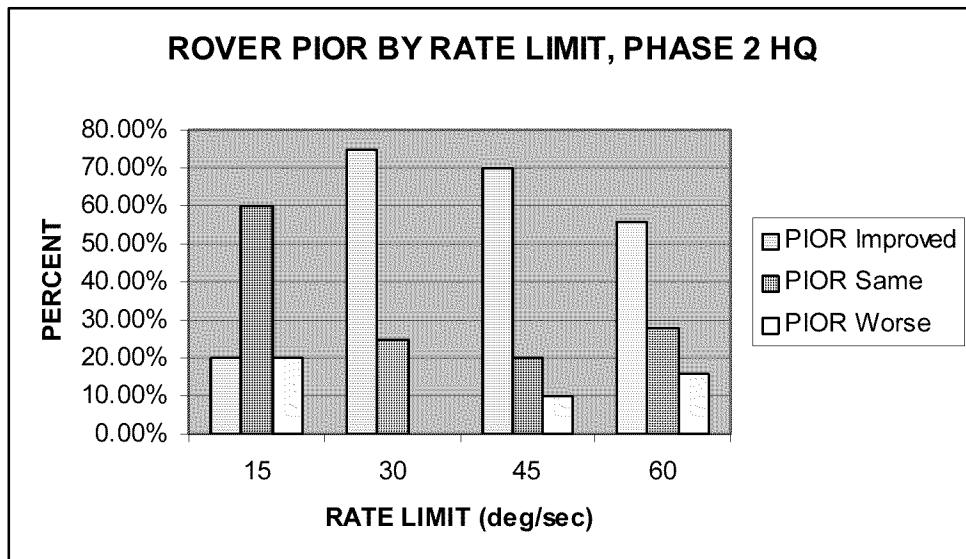


Figure B-39. PIOR Comparison – Rate Limit, HQ 2

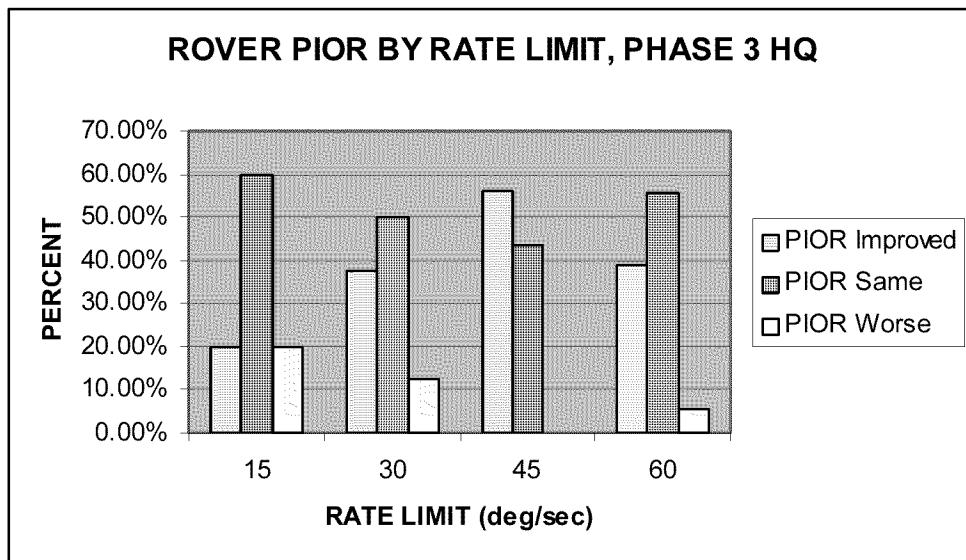


Figure B-40. PIOR Comparison – Rate Limit, HQ 3

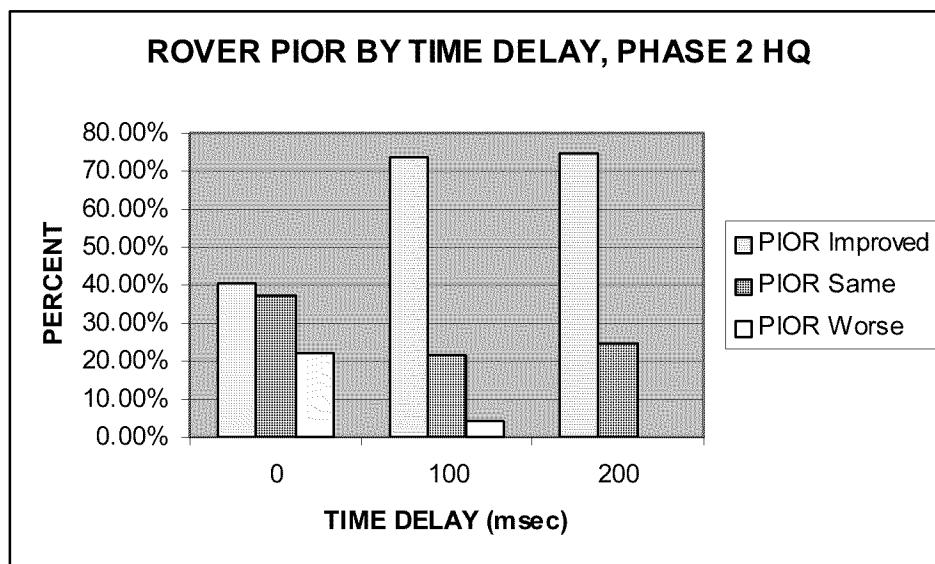


Figure B-41. PIOR Comparison – Time Delay, HQ 2

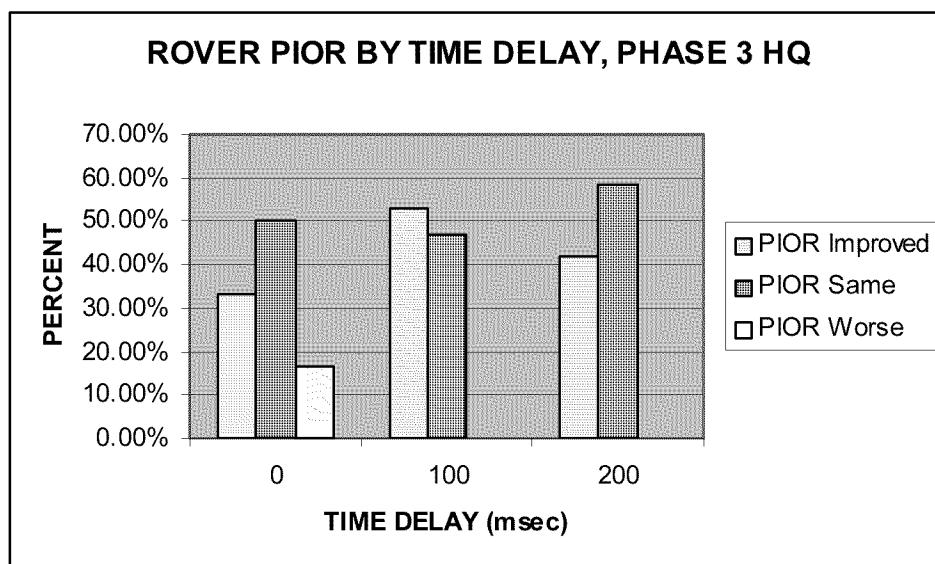


Figure B-42. PIOR Comparison – Time Delay, HQ 3

Test: HAVE ROVER Aircraft: VISTA Flight: 01 Pilot: 1  
Maneuver: Phase 2 HUD Record Number: 24 ROVER: On

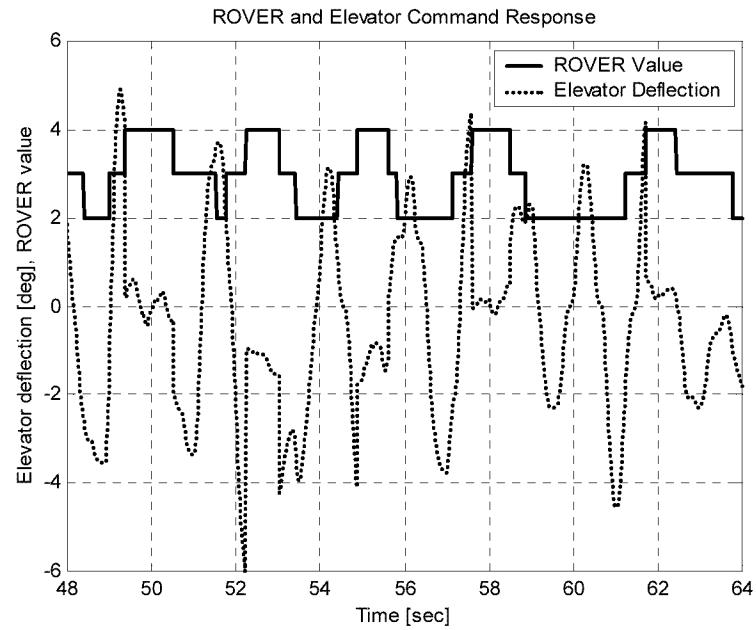


Figure B-43. Elevator Command and RIV (PIOR Improved, HQ 2)

Test: HAVE ROVER Aircraft: VISTA Flight: 7 Pilot: 2  
Maneuver: Phase 2 TGT Record Number: 16 ROVER: On

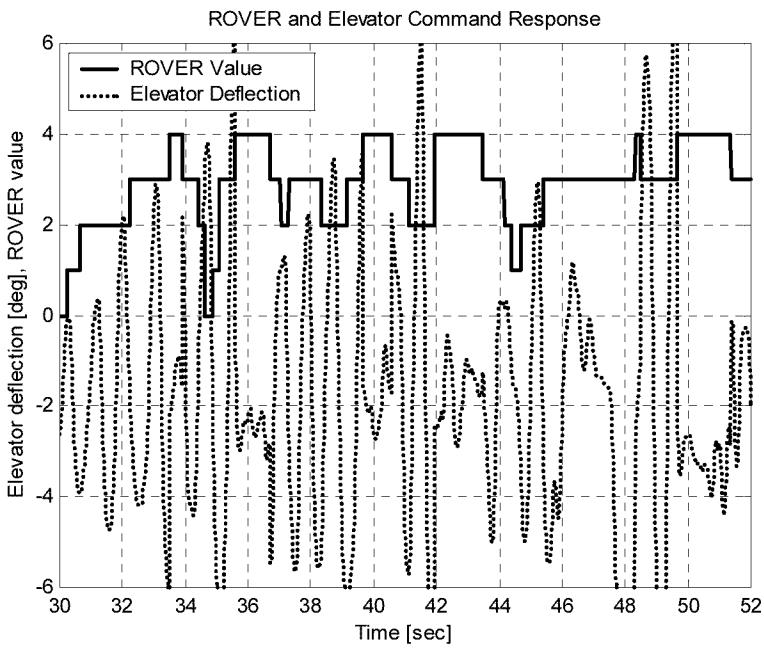


Figure B-44. Elevator Command and RIV (PIOR Same, HQ 2)

Test: HAVE ROVER Aircraft: VISTA Flight: 04 Pilot: 3  
Maneuver: Phase 3 HUD Record Number: 20 ROVER: On

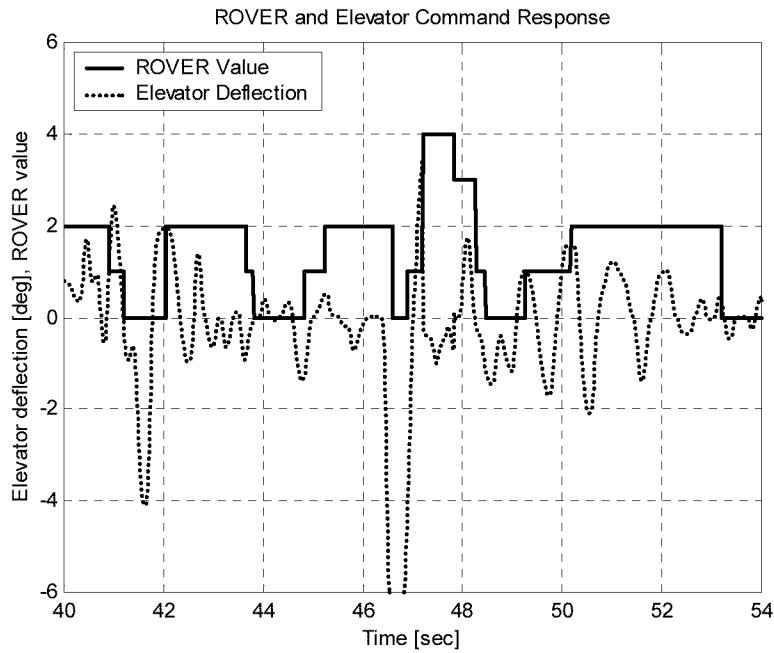


Figure B-45. Elevator Command and RIV (PIOR Improved, HQ 3)

Test: HAVE ROVER Aircraft: VISTA Flight: 04 Pilot: 3  
Maneuver: Phase 3 HUD Record Number: 28 ROVER: On

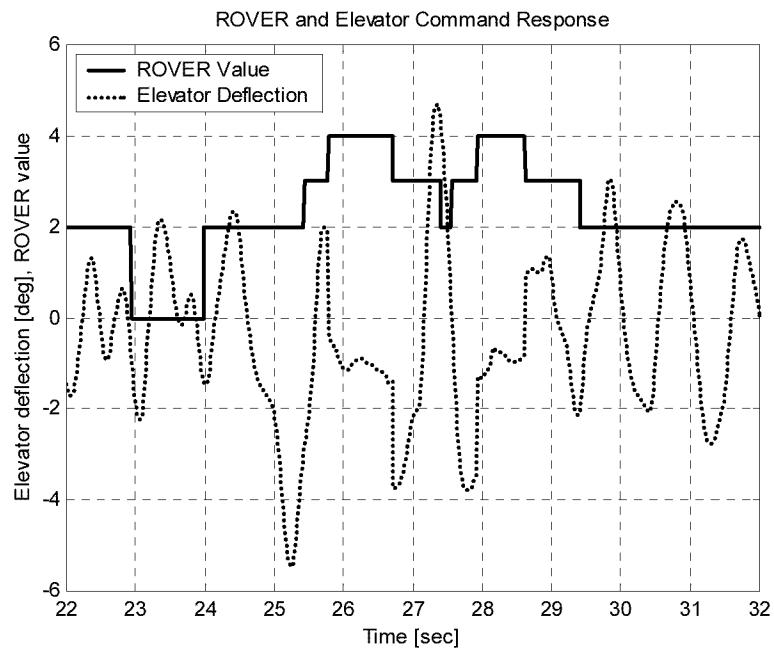


Figure B-46. Elevator Command and RIV (PIOR Same, HQ 3)

Test: HAVE ROVER Aircraft: VISTA Flight: 06 Pilot: 4  
Maneuver: Phase 2 TGT Record Number: 8 ROVER: On

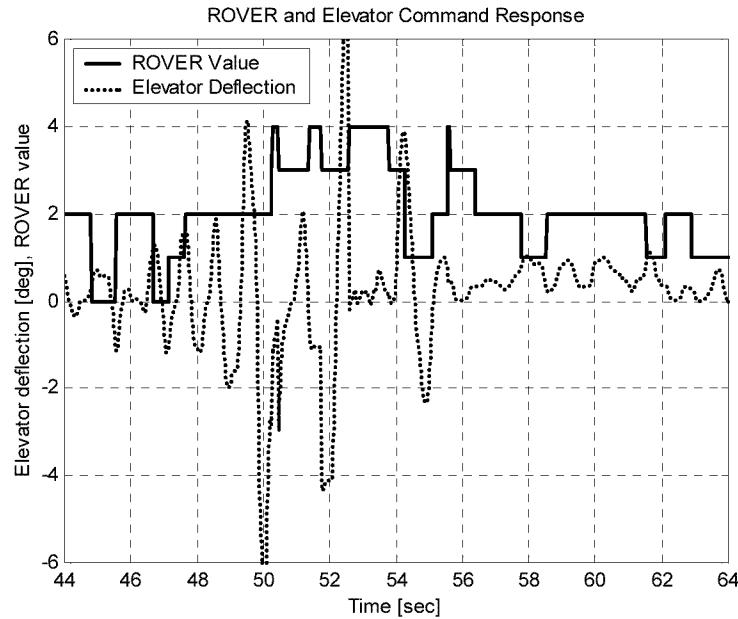


Figure B-47. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 4)

Test: HAVE ROVER Aircraft: VISTA Flight: 01 Pilot: 1  
Maneuver: Phase 2 HUD Record Number: 20 ROVER: On

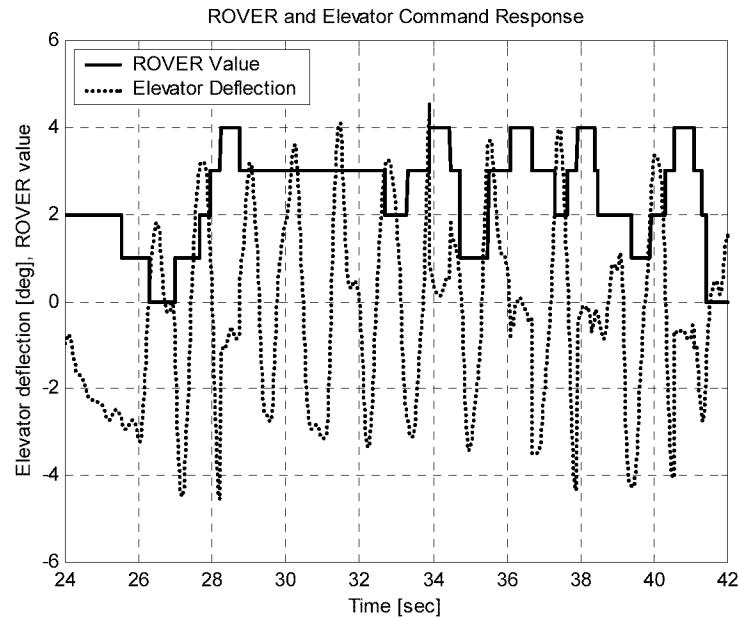


Figure B-48. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 1)

Test: HAVE ROVER Aircraft: VISTA Flight: 04 Pilot: 3  
Maneuver: Phase 2 HUD Record Number: 23 ROVER: On

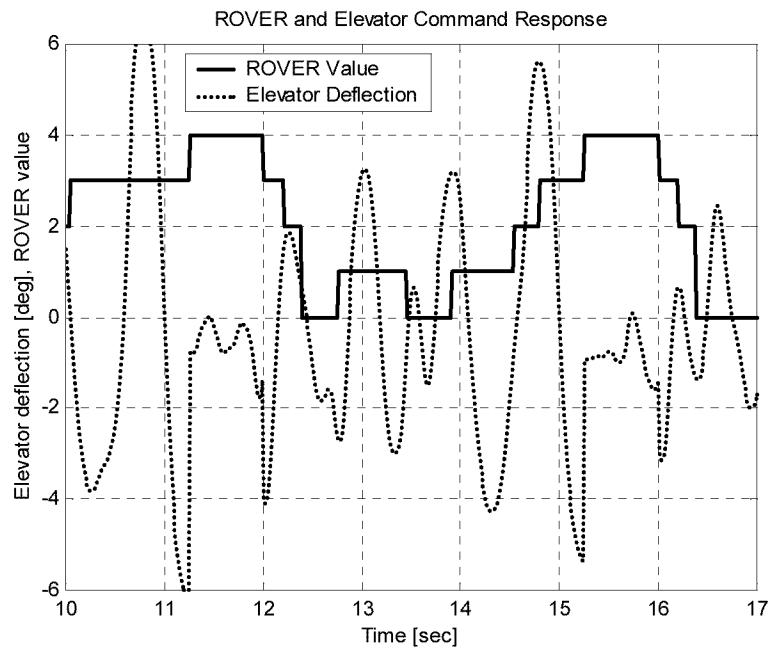


Figure B-49. Elevator Command and RIV (PIOR Worse, HQ 2, Pilot 3)

Test: HAVE ROVER Aircraft: VISTA Flight: 06 Pilot: 4  
Maneuver: Phase 3 TGT Record Number: 15 ROVER: On

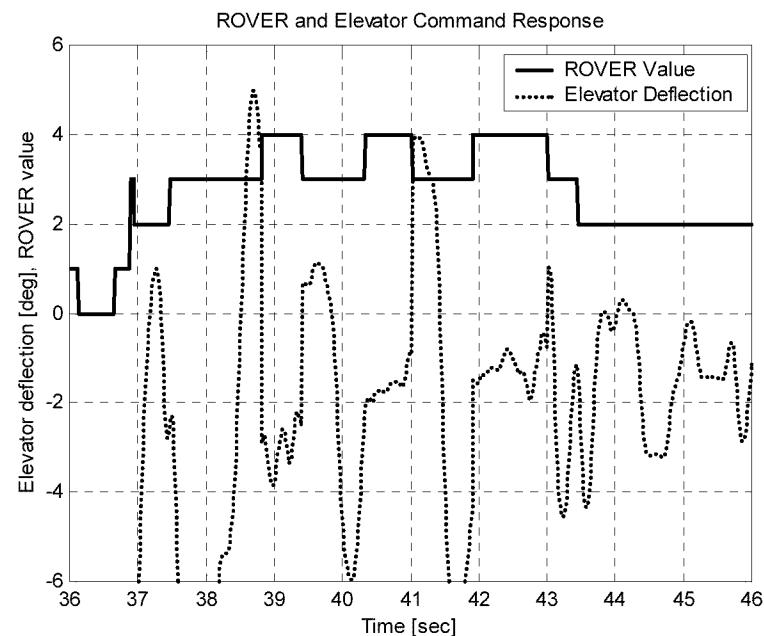


Figure B-50. Elevator Command and RIV (PIOR Worse, HQ 3)

**Confidence level determination:** To determine confidence level of a parameters improvement, the test team calculated the mean and standard deviation of the performance between the ROVER on and ROVER off test points. Using the mean and standard deviations, the test team performed a standard student-T evaluation to get the confidence level of the mean change being higher than zero.

Table B-1. Task Performance Improvement for Different Pilots

Pilot	Performance	Desired score		Adequate score		CHR	
		HUD	Target	HUD	Target	HUD	Target
A	% Improved	36	60	55	60	36	25
	% Worse	55	40	18	40	0	25
	% No Change	9	0	27	0	64	50
	Mean Change	-0.18	-0.60	1.27	1.80	0.82	0
	STD Dev	3.63	8.76	3.20	7.53	1.78	0.76
	% Confidence	-	-	89	73	92	50
B	% Improved	42	75	25	100	33	80
	% Worse	33	25	58	0	0	0
	% No Change	25	0	17	0	67	20
	Mean Change	0.42	3.50	-1.17	5.25	0.42	2.20
	STD Dev	4.21	3.32	4.80	4.65	0.67	2.28
	% Confidence	60	99	-	99	93	99
C	% Improved	78	50	78	50	67	38
	% Worse	0	50	11	50	0	25
	% No Change	22	0	11	0	33	38
	Mean Change	4.22	4.50	3.22	-2.00	1.56	-0.50
	STD Dev	5.33	19.09	3.77	15.56	1.94	2.93
	% Confidence	99	69	99	-	99	-
D	% Improved		67		67		0
	% Worse		33		33		0
	% No Change		0		0		100
	Mean Change		5		3		0
	STD Dev		14		11.14		0
	% Confidence		87		81		-
All pilots	% Improved	52	64	48	71	45	38
	% Worse	29	36	32	29	0	17
	% No Change	19	0	19	0	55	46
	Mean Change	1.52	2.50	0.90	2.50	0.90	0.29
	STD Dev	4.51	9.51	4.36	8.11	1.56	2.18
	% Confidence	96	58	87	60	99	54

Table B-2. Task Performance Improvement for Different Configurations

Config	Performance	Desired score		Adequate score		CHR	
		HUD	Target	HUD	Target	HUD	Target
A	% Improved	60	50	60	50	20	50
	% Worse	20	50	40	50	0	50
	% No Change	20	0	0	0	80	0
	Mean Change	1.00	2.50	2.20	4.00	0.40	0.67
	STD Dev	1.41	4.95	3.56	2.83	0.89	1.15
	% Confidence	91	65	89	80	82	67
B	% Improved	70	67	50	67	60	67
	% Worse	20	33	30	33	0	0
	% No Change	10	0	20	0	40	33
	Mean Change	1.00	2.50	2.20	4.00	0.40	0.67
	STD Dev	1.41	4.95	3.56	2.83	0.89	1.15
	% Confidence	91	65	89	80	82	67
C	% Improved	36	71	36	71	45	29
	% Worse	36	29	36	29	0	29
	% No Change	27	0	27	0	55	43
	Mean Change	-0.27	5	-0.73	4.7	0.45	0
	STD Dev	3.52	10.7	3.82	7.6	0.52	2.77
	% Confidence	-	64	-	68	99	50
D	% Improved	40	50	60	50	40	50
	% Worse	40	50	20	50	0	0
	% No Change	20	0	20	0	60	50
	Mean Change	3.20	-3.5	1.60	-1.5	2.40	0.5
	STD Dev	7.85	13.4	6.43	12.02	3.29	0.57
	% Confidence	80	-	70	-	92	73
All configs	Improved	52	64	48	71	45	38
	Worse	29	36	32	29	0	17
	No Change	19	0	19	0	55	46
	Mean Change	1.52	2.50	0.90	2.50	0.90	0.29
	STD Dev	4.51	9.51	4.36	8.11	1.56	2.18
	% Confidence	96	58	87	60	99	54

Table B-3. Task Performance Improvement for Different Rate Limits

Rate limit (deg/sec)	Performance	Desired score		Adequate score		CHR	
		HUD	Target	HUD	Target	HUD	Target
15	% Improved	0	50	25	50	50	0
	% Worse	75	50	50	50	0	0
	% No Change	25	0	25	0	50	100
	Mean Change	-2.50	4.50	-3.25	1.00	1.75	0.00
	STD Dev	3.11	19.09	4.99	11.31	2.87	0.00
	% Confidence	-	57	-	53	86	-
30	% Improved	57	100	57	100	86	25
	% Worse	14	0	43	0	0	50
	% No Change	29	0	0	0	14	25
	Mean Change	3.71	9.00	1.29	10.33	1.57	-0.50
	STD Dev	6.34	8.89	5.12	5.03	1.99	5.32
	% Confidence	92	75	74	86	0.96	-
45	% Improved	50	67	38	67	25	50
	% Worse	38	33	13	33	0	0
	% No Change	13	0	50	0	75	50
	Mean Change	1.63	1.17	1.63	0.67	0.38	0.75
	STD Dev	4.41	6.97	3.62	7.74	0.74	0.89
	% Confidence	84	55	88	53	90	72
60	% Improved	50	33	38	67	25	44
	% Worse	38	67	13	33	0	22
	% No Change	13	0	50	0	75	33
	Mean Change	1.63	-2.67	1.63	-0.67	0.38	0.33
	STD Dev	4.41	9.61	3.62	8.33	0.74	1.32
	% Confidence	84	-	88	-	90	58
All rate limits	Improved	52	64	48	71	45	38
	Worse	29	36	32	29	0	17
	No Change	19	0	19	0	55	46
	Mean Change	1.52	2.50	0.90	2.50	0.90	0.29
	STD Dev	4.51	9.51	4.36	8.11	1.56	2.18
	% Confidence	96	58	87	60	99	54

Table B-4. Task Performance Improvement for Different Time Delays

Time delay (msec)	Performance	Desired score		Adequate score		CHR	
		HUD	Target	HUD	Target	HUD	Target
0	% Improved	56	57	56	57	44	36
	% Worse	33	43	33	43	0	18
	% No Change	11	0	11	0	56	45
	Mean Change	1.78	0.57	0.00	2.00	1.56	0.55
	STD Dev	6.51	10.67	5.66	8.14	2.55	2.02
	% Confidence	78	52	50	58	95	58
100	% Improved	64	75	57	75	57	25
	% Worse	21	25	29	25	0	13
	% No Change	14	0	14	0	43	63
	Mean Change	1.79	5.25	1.86	2.25	0.79	-0.38
	STD Dev	3.40	11.44	4.00	11.70	0.89	2.83
	% Confidence	97	64	95	56	99	-
200	% Improved	25	67	25	100	25	60
	% Worse	38	33	38	0	0	20
	% No Change	38	0	38	0	75	20
	Mean Change	0.75	3.33	0.25	4.00	0.38	0.80
	STD Dev	4.03	4.51	3.45	4.36	0.74	1.30
	% Confidence	69	70	58	74	90	68
All time delays	Improved	52	64	48	71	45	38
	Worse	29	36	32	29	0	17
	No Change	19	0	19	0	55	46
	Mean Change	1.52	2.50	0.90	2.50	0.90	0.29
	STD Dev	4.51	9.51	4.36	8.11	1.56	2.18
	% Confidence	96	58	87	60	99	54

## Appendix C: Flight Test Log, Rating Scales, and Pilot Comments

Table C-1. Flight Test Log

<b><u>VISTA SORTIES</u></b>					
<u>Flight No.</u>	<u>Mission No.</u>	<u>Date</u>	<u>FCP</u>	<u>RCP</u>	<u>Duration (Hrs)</u>
Val.Flt	717	05 Oct 01	Johnson	Peer	1.2
1	718	09 Oct 01	Ballance	Peer	1.2
2	719	09 Oct 01	Maurizio	Peer	1.2
3	720	10 Oct 01	Maurizio	Peer	1.2
4	721	10 Oct 01	Johnson	Peer	1.2
5	722	11 Oct 01	Johnson	Peer	1.2
6	723	11 Oct 01	Thurling	Peer	1.2
7	724	12 Oct 01	Maurizio	Peer	1.2
8	725	15 Oct 01	Ballance	Peer	1.2
9	726	16 Oct 01	Johnson	Peer	1.2
10	727	16 Oct 01	Ballance	Peer	1.2
11	728	17 Oct 01	Ballance	Peer	1.2
12	729	17 Oct 01	Maurizio	Peer	1.2

<b><u>T-38 TARGET SORTIES</u></b>					
<u>Flight No.</u>	<u>VISTA Mission No.</u>	<u>Date</u>	<u>FCP</u>	<u>RCP</u>	<u>Duration (Hrs)</u>
1	722	11 Oct 01	Rosepink	Shaferman	1.2
2	723	11 Oct 01	Rosepink	Bailey	1.2
3	724	12 Oct 01	Ballance	Bailey	1.2
4	726	16 Oct 01	Maurizio	Cali	1.2
5	727	16 Oct 01	Johnson	Shaferman	1.2
6	728	17 Oct 01	Johnson	Cali	1.1

<b>Total VISTA</b>	<b>15.6</b>
<b>Total Target</b>	<b>7.1</b>
<b>Total</b>	<b>22.7</b>

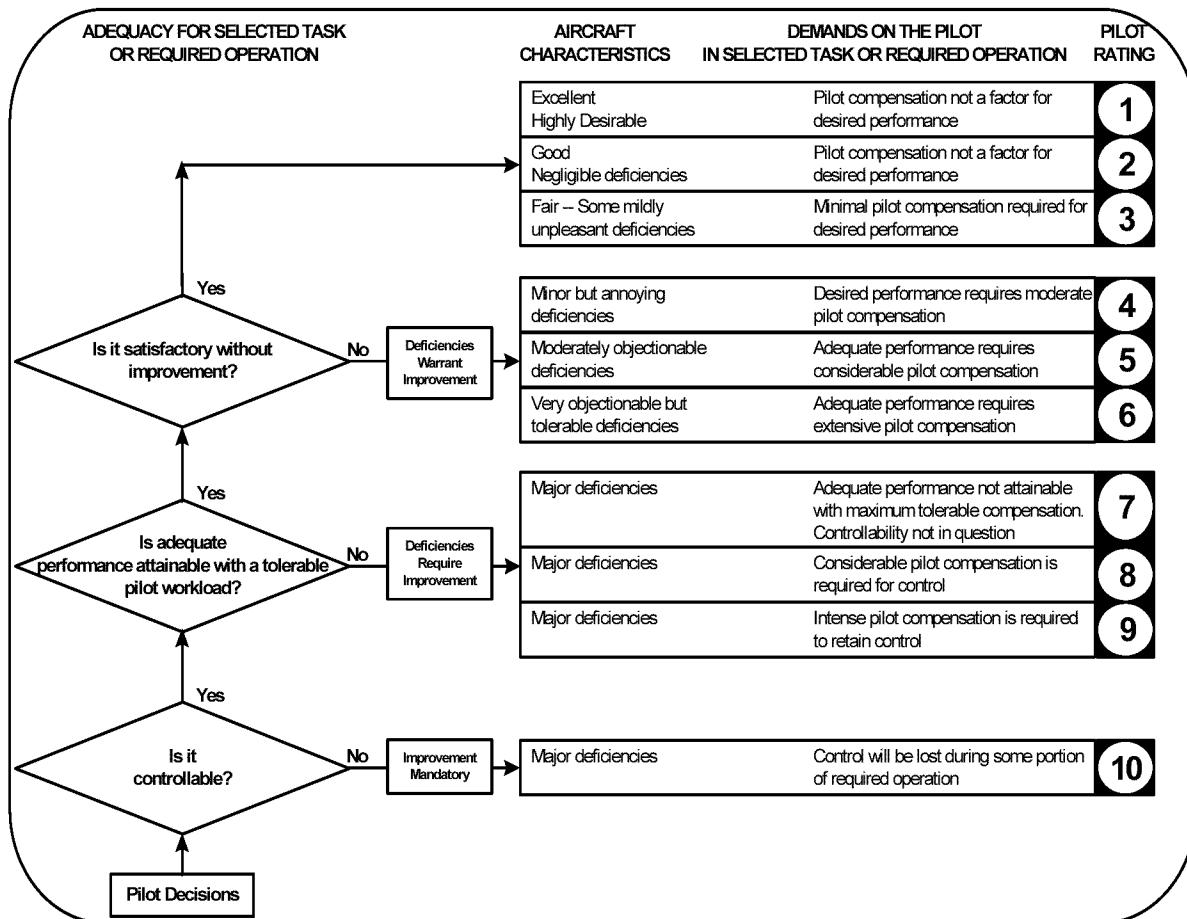


Figure C-1. Cooper-Harper Rating Scale

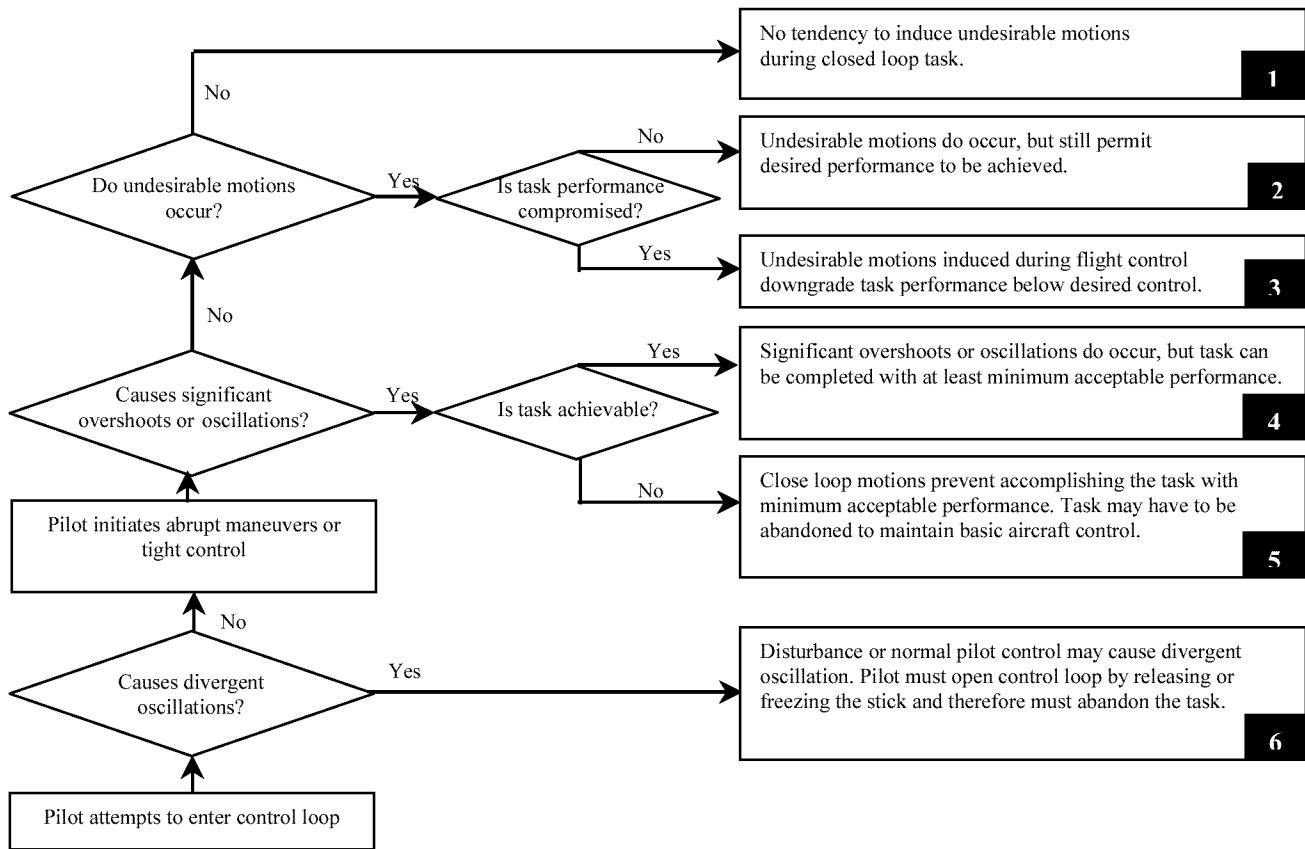


Figure C-2. Pilot-Induced Oscillation Rating (PIOR) Scale

Type 1 nuisance rating (not more than 10% of the test points)  
ROVER did not activate when the pilot perceived a PIO  
(PIOR  $\geq 4$  & RIV  $< 4$ )  
\*\* This is a safety/reliability problem\*\*

Type 2 nuisance rating  
ROVER activations were timely and did not result in a negative pilot comment  
(PIOR  $\leq 3$  & RIV  $\leq 3$  or PIOR  $\geq 4$  & RIV = 4)

Type 3 nuisance rating (not more than 20% of the test points)  
ROVER activated at a time when the pilot felt the aircraft was not in a PIO  
(PIOR  $\leq 3$  & RIV = 4)  
\*\* This is the true nuisance\*\*

Figure C-3. Nuisance Rating (NR) Scale

## Pilot Comments and Ratings

### Data Flight 1: Pilot 1, 19 Oct 2001

**Configuration Q:** (Case A, 60 deg/sec, and 0 msec delay). This felt like a “good aircraft”. Phase 2 tasks resulted in a bounded oscillation about the target with no sign of divergence in pitch. Phase 3 tracking was straight forward, with just some minor movement about the target when attempting fine tracking. With ROVER on there were no changes in the phase 2 and 3 tasks, there were no ROVER activations and none were expected. A lower PIO rating was given for the phase 3 task ROVER on and this was probably due to familiarity with the configuration allowing better close tracking. The tracking task was interrupted for approx 5 secs due to lose of HUD symbology looking into the sun.

**Configuration H:** (Case C, 45 deg/sec, and 0 msec delay). Felt “more sluggish in pitch”. During phase 1 and 2 there were “no overshoots, can stop it where I want it”. Phase 3 there were some overshoots on big inputs but fine tracking was OK. During phase 1,2 and 3 with ROVER on there was no change. There were no ROVER engagements and the lower PIO ratings probably reflect increasing familiarity with the configuration.

**Configuration O:** (Case B, 45 deg/sec, and 200 msec delay). Phase 1 felt “jumpy”, oscillated around when in the loop. Phase 2 was divergent. Phase 3 was “much more difficult” as it was easy to drive oscillations around the target. Task terminated after 65 secs due to area boundary. Phase 2 ROVER on resulted in “timely” activations when rapid motions started to build up, with no problems continuing with inputs when ROVER disengaged. Small phase 2 inputs resulted in several oscillations before increasing rates/movement activated ROVER, therefore PIO rating 5. Phase 3 task ROVER on, ROVER activated at “timely” points on large motions and didn’t cause any control problems when disengaging. The configuration was still very susceptible to moderate “bubbles” around the target without ROVER activation so ROVER didn’t actually improve the ratings.

**Configuration C:** (Case A, 15 deg/sec, and 0 msec delay). Felt “more predictable than last one(O)”, however it was “slow on big inputs” but “easy to stop where wanted”. Phase 3 there was a “slight tendency to overshoot”, it was “easy to track” and big inputs caused a “bobble” about the target. Phase 2 ROVER on resulted in a nuisance rating of 3 as when making a big input to get a big response ROVER engaged giving the impression to the pilot that it “slowed down getting there” and that there were no oscillations. Phase 3 ROVER on there were no ROVER engagements noted or desired, ratings and scores were similar to ROVER off.

Pilot technique was changed during configuration N to make bigger inputs on phase 2.

**Configuration N:** (Case D, 45 deg/sec, and 0 msec delay). Felt “strange”, “starts but then slows”. Phase 2 not divergent. Phase 3 just the occasional overshoot. Phase 2 ROVER on big inputs resulted in ROVER activation “straight away” which felt too early when trying to get a big motion. Phase 3 there were no ROVER activations and none were needed.

**Configuration E:** (Case A, 60 deg/sec, and 200 msec delay). Felt “unpredictable”, got overshoots even in phase 1. Phase 2 definitely diverging. Phase 3 overall control was reasonable but “very hard in tight tracking with many overshoots back and forth across the target”. Phase 2 ROVER on gave many engagements for abrupt big inputs, these felt timely as they would limit any divergence and disengaged at a time that enabled the pilot to easily continue with the task. Phase 3 ROVER on there were numerous engagements, on a few of these it was felt that ROVER engaged early but mostly they were timely on big inputs, stopping a PIO and leaving the piper near the target to continue tracking. The configuration was still difficult to fine track with oscillations back and forth across the target.

## **Data Flight 2: Pilot 2, 9 Oct 2001**

**Configuration Q:** (Case A, 60 deg/sec rate limit, and 0 msec time delay) While flying this configuration the pilot didn't note any particular deficiencies. All motions were predictable and tracking was accurate, either gross acquisition and fine tracking. The test chose the best configuration available for the first test point to get the pilot more acquainted with the task and comply with the build up approach as written in the test plan.

**Configuration J:** (Case C, 45 deg/sec rate limit, and 100 msec time delay) During phase II tracking with ROVER off the pilot felt the oscillations growing and undamped. He often had to ease off control forces in order to prevent large overshoots. Fine tracking was characterized by a bubble of approximately 10 to 15 mrads. With ROVER engaged the filter kicked in several times while performing phase II tracking. It appeared to the pilot the activation was timely and prevented large overshoot freezing the pipper fairly close to the target. During phase three the filter activated only once when the HUD tracking task moved the target symbol quite aggressively. The rest of the task was characterized by the same annoying bubble, which prevented to achieve desired performances. Adequate performances were obtained but with extensive pilot workload. For this reason CHR was 7 in both cases.

**Configuration L:** (Case C, 30 deg/sec rate limit, and 0 msec time delay) This configuration was characterized by nice handling qualities during tracking. During all tracking tasks the pilot assigned a PIOR of 2 and CHR of 3. During phase II with ROVER on the notch filter kicked in several times too early, even if the pilot never experienced PIO at all, resulting in NR of 3 and increasing pilot gain.

**Configuration M:** (Case D, 60 deg/sec rate limit, and 0 msec time delay) During phase II tracking the pilot experienced large amplitude oscillations, which appeared to be bounded. Only once he felt the need to ease off tight control to prevent oscillations to grow too much. Phase III didn't exhibit any bad characteristic. Fine tracking was nice and predictable. Phase II tracking with ROVER activated reduced noticeably the amplitude of the oscillations allowing the pilot to track assiduously the target without backing off the controls. During phase III with ROVER on the filter never activated and the tracking task was almost identical to the one with ROVER off.

**Configuration D:** (Case C, 60 deg/sec rate limit, and 0 msec time delay) The pilot noticed large oscillations during phase II tracking, however he never had the feeling that they were growing. For this reason he always stayed in the loop and assigned a PIOR of 4. Phase III was characterized by smooth fine tracking and predictable aircraft trajectories. The pilot noticed that if he kept applied smooth and low frequency inputs hardly any oscillation was experienced. As soon as he entered tight control with aggressive corrections the oscillations would grow in amplitude but still remain bounded. After the filter was selected on it activated several time upon large pilot inputs preventing oscillations to grow and keeping aircraft pipper fairly close to the HUD target. Phase III required only low frequency inputs and any ROVER activation was noted.

**Configuration B:** (Case D, 30 deg/sec rate limit, and 0 msec time delay) During this configuration the pilot noticed the very nice fine tracking characteristics. Transitioning to phase II the pilot was really surprised on how fast the aircraft oscillations diverged leading to a VSS trip. The VSS tripped at approximately -0.7 Gs and few seconds after large phase two inputs. The pilot commented that this configuration was "very subtle". When the ROVER filter was activated, phase II tracking became less "sporty". The pilot noticed that the filter remained engaged for several seconds while he was keeping low frequency inputs. ROVER deactivated noticeably faster when if the pilot released the controls as soon the PIO symbol appeared in the HUD. Phase III was characterized by nice fine tracking characteristic and predictable aircraft motions. The configuration exhibited bad characteristics only when the pilot inputs' were at high frequency and large amplitude.

**Configuration Z:** (Case C, 30 deg/sec rate limit, and 100 msec time delay) phase I tracking was characterized by fairly large bubble of approximately 15 mrad. Precise tracking was difficult and requested a big amount of pilot compensation. Phase II with ROVER off led to a VSS pitch monitor trip due to the increasing amplitude of the oscillations. The pilot felt the PIOS, and would have appreciated the ROVER intervention to damp those off. Phase II with ROVER engaged led to a PIOR of 4 due to the reduction in oscillations' amplitude. As forecasted from phase I, phase III was characterized by extensive pilot's compensations trying to damp out the small oscillations around the target. The pilot noted that was very difficult to achieve precise pitch changes too.

### **Data Flight 3: Pilot 2, 10 Oct 2001**

**Configuration E:** (Case A, 60 deg/sec rate limit, and 0 msec time delay) During phase II tracking with ROVER off the pilot experienced fairly large amplitude oscillations, which appeared to be bounded. PIOR was 4. During phase III the pilot reported the presence of an annoying bubble around the target, which made fine tracking fairly difficult if not impossible. Phase II tracking with ROVER on still produced bounded oscillations but it appeared that the amplitude was slightly reduced. Timely activation of ROVER during phase III, which kept again the oscillations to a smaller amplitude. Fine tracking was still unsatisfactory leading to the same CHR value recorded with ROVER off.

**Configuration H:** (Case C, 45 deg/sec rate limit, and 0 msec time delay) This configuration was characterized by nice handling qualities during tracking. During all tracking tasks the pilot assigned a PIOR of 2 and CHR of 3. During phase II with ROVER on the notch filter kicked in several times too early, even if the pilot never experienced PIO at all, resulting in NR of 3 and increasing pilot gain.

**Configuration O:** (Case B, 45 deg/sec rate limit, and 200 msec time delay) During phase II the pilot experienced large amplitude oscillations that appeared to be divergent and felt the need to ease tight control to prevent aircraft departure. Fine tracking was very imprecise and still fairly big oscillations were almost impossible to damp. In several occasions the pilot felt to be off phase with the aircraft motion. With the activation of ROVER the pilot still experienced fairly big oscillations but this time they appeared to be bounded even keeping tight control. During phase III the pilot fine tracking was still poor due to small amplitude oscillations completely undamped.

**Configuration N:** (Case D, 45 deg/sec rate limit, and 0 msec time delay) The aircraft showed nice handling qualities during tracking. While performing phase II the pilot inputs were from stop to stop and still the oscillations were moderate, bounded, and damped. Phase III exhibit nice fine tracking characteristics even during quick and aggressive pipper repositioning. Even if almost not required Rover kicked in timely during phase II leading to smaller amplitude oscillations than with rover off and bounded around the target. During phase III rover never kicked in.

**Configuration C:** (Case C, 15 deg/sec rate limit, and 0 msec time delay) During this configuration the pilot noticed the very nice fine tracking characteristics. Transitioning to phase II the pilot was really surprised on how fast the aircraft oscillations diverged leading to a VSS trip. The VSS tripped at approximately -1.2 Gs and few seconds after large phase two inputs. The pilot commented that this configuration was "very subtle". During phase II with Rover on the pilot experienced several timely filter activations. When Rover kicked in the pilot kept low frequency stick input and once, when Rover faded out the aircraft oscillations became unbounded leading to a VSS trip. During phase III with Rover off extensive pilot compensations were required to prevent the aircraft from diverging oscillations. This wasn't necessary when Rover was on because either the filter or minor pilot compensations prevented the oscillations to grow. Still nice handling qualities during fine and gentle tracking.

**Configuration V:** (Case D, 15 deg/sec rate limit, and 0 msec time delay) Very subtle configuration. During gentle fine tracking aircraft responses were predictable and accurate. As soon as the pilot increased the

amplitude of the stick inputs it appeared that the “aircraft couldn’t handle it anymore” resulting in a pitch monitor VSS trip. Same considerations were applicable for phase III with Rover off. When the filter was activated it appeared that it kicked in timely and fairly adequately. Unfortunately when the filter faded out, if the pilot was holding low frequency stick input the aircraft departed. The VSS tripped due to a pitch monitor caused by the divergent oscillations both during phase II and phase III tracking. Pilot assigned PIR of 6 to all tracking task and, when applicable CHR of 10 due to the lost of aircraft control.

**Configuration I:** (Case B, 45 deg/sec rate limit, and 100 msec time delay) The configuration exhibits nice handling qualities during fine tracking. All the oscillations experienced during phase II were bounded and of moderate amplitude. The pilot would have used the help of rover couple of time to keep the magnitude of the oscillations little bit smaller and closer to the pipper. With Rover on the pilot experienced oscillations with lower frequency and smaller amplitude. During phase III the pilot noticed timely rover activation during large amplitude oscillations but it appeared the rover was unable to reduce small amplitude ones. The precise time and conditions in which the pilot would have liked Rover to be activated are noted on the strip charts.

#### **Data Flight 4: Pilot 3, 10 Oct 2001**

**Configuration D:** During D (Case C, 60 deg/sec, and 0 msec delay), the pilot observed “small/mild bobbles, but no significant oscillations” while fine tracking. PIO ratings of 2 were recorded for both phase 2 and phase 3 maneuvering. “Gross acquisition/aggressive pulls drove “PIO” but I felt I was still in phase with aircraft response.” This comment drove a Nuisance Rating of 3. Threshold values were set at the standard level for this evaluation.

**Configuration B:** During B (Case D, 30 deg/sec, and 0 msec delay), the crew experienced a pitch monitor VSS trip as the aircraft oscillated from +2.5 to -0.2 G’s. “I needed ROVER’s help on that one.” Phase 3 also forced a VSS trip when ROVER was disengaged. The pilot commented, “smooth fine tracking”, but large gross acquisitions drove divergent oscillations. The pilot got out of the loop on one early oscillation, then 30 seconds later, a pitch monitor VSS trip disengaged the VSS a -2.3 G’s. Both of the above received a PIOR of 6.

ROVER increased performance and reduced both the PIOR and CHR for the phase 3 task. During phase 2 the pilot reported early “PIO” activations initially but then most were timely and necessary. ROVER’s overall effectiveness and timeliness was assessed as good. For fine tracking during phase 3, the aircraft displayed smooth fine tracking, good “PIO” activations as the pilot stayed in the loop during undesirable oscillations, and several events were recorded as the pilot noted timely activations. Compensation methods required included slower gross acquisition to prevent very large overshoots and oscillations.

**Configuration J:** During J (Case C, 45 deg/sec, and 100 msec delay), the pilot first commented that the aircraft displayed “quick initial response”. However, upon tape review, the time delay was driving the pilot to make larger inputs due to the lack of initial aircraft response with the time delay, so the first seen response was actually due to large stick inputs. The aircraft displayed a “jerky response”. During phase 2 maneuvers, a pitch monitor VSS trip interrupted the task – PIOR 6. “Slight pitch bobbles” and mild oscillation was noted during phase 3 tracking. The pilot commented, “undesirable fine tracking” and “occasionally I had a bounded oscillation around the target of about +/- 15 mils”.

ROVER again reduced the PIOR and CHR numbers while driving no nuisance reports from the pilot. Phase 2 maneuvers – “divergent oscillations damped by ROVER”, “timely activations”, and “ROVER appeared to prevent the VSS trips experienced earlier”. Phase 3 tracking showed a modest increase in desired and adequate scores and a single unit increase in CHR from 7 to 6. This is noteworthy because this transitioned from a level 3 aircraft to level 2 performance and workload. The pilot still had an undesirable configuration and made the following comment, “very undesirable bobbles in fine tracking” and multiple “PIO” activations. Post-flight tape review showed fine tracking bobbles of +/- 10 mils.

**Configuration Z:** During Z (Case C, 30 deg/sec, and 100 msec delay), only the phase 2 maneuvering without ROVER drove a pitch monitor VSS trip. The pilot commented, “I could feel the divergent oscillation and was waiting for ROVER or the VSS trip.” Phase 3 tracking saw “undesirable/annoying pitch bobbles in fine tracking”. Tape review highlighted 20 mil overshoots during gross acquisition. The pilot compensated by making small initial inputs to try to reduce the amplitude of the overshoots.

ROVER on phase 2 maneuvers again saw “significant overshoots” and apparent divergent oscillations of +/- 50 mils during 4 overshoot cycles. “As the amplitude grew, ROVER engaged and damped the oscillations within about 1 second.” The system was manually disengaged and received a PIOR of 5. Phase 3 tracking again highlighted the configurations tendency to pitch bobble. A +/- 5-mil oscillation was seen during post flight. This drove “considerable compensation” and a CHR of 5. The first ROVER activation was reported as early, but follow-on engagements were not considered a nuisance.

**Configuration L:** During L (Case C, 30 deg/sec, and 0 msec delay), the pilot reported significant oscillations and requested ROVER’s assistance. He backed out of the loop during a slowly divergent oscillation and assigned a PIOR of 5. Gross acquisition during phase 3 tracking was sluggish. The aircraft was smooth in fine tracking with small bobbles of +/- 2-4 mils.

ROVER engaged maneuvers highlighted “timely ‘PIO’ engagements”. The aircraft continued to display “smooth fine tracking” with only 1 ROVER activation during a large amplitude gross acquisition. The pilot evented as appearing to be a nuisance activation, but upon tape review, the “PIO” engaged during a 20-mil overshoot gross acquisition and lasted for only a fraction of a second. The end result was a gross acquisition input then ROVER/the SAS brought the pipper right back within 5 mils of the target as ROVER disengaged. During flight a NR of 3 was assigned but was later changed to a 2 during tape review.

**Configuration M:** During M (Case D, 60 deg/sec, and 0 msec delay), the pilot felt a quickly responding configuration that stayed in-phase. “I felt the aircraft stayed in phase throughout the phase 2 task.” Phase 3 tracking generated the comment, “someone just gave me a Viper to track with” and “highly desirable in fine tracking”. The aircraft was also nice in gross acquisition with very small overshoots – PIOR of 1 and CHR of 1.

ROVER active tasks did not improve performance – one engagement during phase 2 maneuvering actually precipitated a NR of 3 – “That was an unexpected ROVER activation!” Since no “PIO” engagements were recorded during phase 3 tracking, this set of data points should not be used to calculate overall ROVER enhancement during this test plan.

**Configuration Y:** During Y (Case B, 60 deg/sec, and 100 msec delay), a pitch monitor VSS trip terminated phase 2 maneuvers. The pilot observed a slowly divergent oscillation. “I could feel it building up to the VSS trip.” Approximately 5 complete cycles were observed – the VSS tripped at approximately -0.6G’s. Multiple events were recorded during phase 3 tracking with ROVER disengaged – “This configuration is highly undesirable” and “airspeed suffered as I spent more time/energy on the task itself.” The pilot recorded adequate performance and assigned a PIOR of 5 and a CHR of 8.

During ROVER engaged maneuvering, the pilot still experienced undesirable oscillations – “ROVER did a good job in preventing divergence.” The phase 3 tracking prompted the following comment, “When the ROVER activations were close together, the second one usually felt unnecessary.” Both the PIOR and CHR improved with ROVER engaged.

**Configuration W:** During W (Case A, 60 deg/sec, and 100 msec delay), the pilot felt the aircraft stayed in phase longer than previous configurations. One event was recorded during phase 2 and the pilot said some of the oscillations felt bounded while some felt slowly divergent. Tape review showed bounded oscillations of +/- 50 mils and +2.5 to -1.0 G’s. A PIOR of 5 was assigned. Phase 3 was

plagued with multiple pitch bobbles and overshoots of +/- 15 mils. “Fine tracking is difficult with a high workload to try to damp the bounded oscillations.” A CHR of 6 and PIOR of 4 were assigned.

ROVER suppressed most of the large amplitude oscillations during phase 2, but “It felt like early “PIO” but ROVER did suppress the oscillation and kept all oscillations bounded by +/- 25 mils.” About half of the activations were reported as slightly earlier than desired. Upon tape review, no NR was assigned. A modest improvement to tracking scores was achieved with ROVER engaged during phase 3 tracking. The aircraft still displayed “undesirable pitch bobbles”. Two ROVER activations were recorded and a PIOR of 2 and CHR of 4 were assigned.

### **Data Flight 5: Pilot 3, 11 Oct 2001**

**Configuration I:** During I (Case B, 45 deg/sec, and 100 msec delay) with a T-38 target in a level turn between 2-4 G’s, the test aircraft displayed slowly growing divergent amplitude in phase 2 maneuvering. The pilot reported pitch sensitivity, but this was likely due to the 100 msec delay. For phase 3, it was difficult to fine track with bounded bobbles. “There was an initial tendency to overshoot in gross acquisition.” The pilot achieved mostly adequate performance and assigned a CHR of 5.

ROVER engaged during the phase 2 task and prevented the large amplitude overshoots seen earlier. These engagements reduced the overall oscillations – PIOR of 3. During the phase 3 task, ROVER engaged during the gross acquisition and damped a large amplitude overshoot. Fine tracking exhibited annoying pitch bobbles of +/- 10 mils.

**Configuration J:** During J (Case C, 45 deg/sec, and 100 msec delay), phase 2 maneuvering resulted in fairly quickly growing divergent oscillations and a pitch monitor VSS trip – PIOR of 6. The VSS also tripped off during phase 3 maneuvering during the gross acquisition as the AOA increased to approximately 15 degrees. A repeat of this using slightly less roll control on the reposition resulted in large overshoots during gross acquisition, but no VSS safety trip. Fine tracking was difficult as large bobbles of +/- 10 mils were always present. The pilot commented that a lot of lead compensation was required to try to overcome the bobbles – CHR of 6 and PIOR of 3.

With ROVER active, several timely engagements were observed during phase 2 maneuvering – PIOR of 3. The phase 3 task was flown 3 times as the rolling reversal maneuvering during gross acquisition twice led to a hardover VSS trip. The third maneuver was flown to nearly 0 G on the reversal and did not trip off the system. The pilot experienced very undesirable bobbles during fine tracking and achieved adequate performance – CHR 6 and PIOR of 4. Since no “PIO”/ROVER engagements were observed during the phase 3 tasks, this data point should not be used to compare tracking performance. Phase 2 tasks did show a marked improvement in PIO ratings.

**Configuration Z:** During Z (Case C, 30 deg/sec, and 100 msec delay), a PIOR of 6 was assigned as the pilot observed a slowly growing, divergent PIO of +2.7 to -0.6 G’s as the VSS pitch monitor disengaged the system. Phase 3 fine tracking was again difficult. The aircraft displayed “lateral oscillations – control harmony problems” and pitch bobbles that required considerable compensation. It was interesting to note that the roll characteristics did not change between trials, but a poorly handling aircraft in pitch can exhibit poor lateral handling qualities also.

With ROVER active, “timely activations prevented divergent oscillations”. During phase 3, no “PIO” engagements were observed so no real comparison exists. There appeared to be a learning curve with respect to the lateral problems as the control harmony and pitch bobbles led to smaller oscillations than the previous trial. Only small elevator deflections were required to compensate for the pitch bobbles and target maneuvers, so ROVER activations during this type of fine tracking task is unlikely.

**Configuration V:** During V (Case D, 15 deg/sec, and 0 msec delay), several VSS trips were experienced. Phase 2 maneuvering resulted in a PIOR of 6 as slowly growing, divergent oscillations led to a pitch monitor trip a +2.5 G’s and nearly 15 degrees nose high. “I could definitely tell the trip was coming.” The pilot achieved desired performance during the phase 3 fine tracking and

experienced fewer pitch bobbles than previous configurations. The pilot observed, “It felt quick/snappy in roll”. This comment is most likely due to the slow nature of the pitch rate that made the roll rate appear quick.

Phase 2 with ROVER active resulted in “timely, desirable ROVER activations”. The first activation was quite long (approximately 2 seconds). The pilot commented that the pitch rate was extremely slow with and without ROVER. Phase 3 gross acquisition 3 times led to a VSS safety trip. The pilot attempted to reduce the rolling input during the gross acquisition and was able to pull to realign fuselages but hit an AOA limit at 4.5 G’s while pulling the pipper to the target. No “PIO” engagements were observed and no significant oscillations or overshoot were observed. The pitch monitor anticipated the unstable nature of this configuration when the pilot was pulling on the limiter and disengaged the system before the oscillation developed. A PIOR of 6 was assigned to the phase 3 task.

**Configuration C:** During C (Case C, 15 deg/sec, and 0 msec delay), the pilot experienced a divergent oscillation in phase 2 and terminated the task prior to a VSS trip – PIOR of 6. “Small bobbles and oscillations” were observed during fine tracking of phase 3; however, the pilot again commented that very small stick inputs were required to achieve the fine tracking solution.

ROVER active phase 2 resulted in timely activations and bounded oscillations of +/- 25 mils – PIOR 3. Phase 3 gross acquisition forced a ROVER engagement and a “nice, timely” comment from the pilot. The engagement was on the first pull to the target’s 6 o’clock and left the VISTA nearly 10 degrees behind the target when ROVER kicked back off. This was undesirable but did not lead to another ROVER engagement. No “PIOs” were observed during the fine tracking, so no changes in ratings were assigned – CHR of 5 and PIOR of 2.

**Configuration V:** During V (Case D, 15 deg/sec, and 0 msec delay) with the HUD tracking task, PIOR of 6 was the rating of the day. Phase 2 maneuvering quickly resulted in divergent oscillations and a pitch monitor VSS trip. Phase 3 also resulted in a pitch monitor trip shortly after beginning the task. “This is a very undesirable configuration.”

ROVER did engage during the next set of phase 2 maneuvers; however, the VSS was eventually driven to a negative G safety trip. The pilot observed 4 discrete ROVER engagements that were all deemed as timely and desired. During the second one, the pilot remarked, “Boy that [ROVER] just barely saved it”. The third engagement was timely but lasted over 3 seconds. Immediately following the fourth ROVER deactivation, a pitch monitor VSS trip occurred. While ROVER was active, the pilot was able to complete a significantly larger part of the task before the VSS disengaged.

### **Data Flight 6: Pilot 4, 11 Oct 2001**

**Configuration B:** (Case D, 30deg/sec rate limit, 0 msec time delay) ROVER Off: Sidestick axis coupling apparent in phase 1 maneuvers. Heave response somewhat objectionable as was lateral-directional handling qualities. Handling qualities sensitive to pilot aggressiveness. Mild divergence seen in phase 2 synchronous inputs. Gross acquisition in phase 3 produced a slight oscillation that the pilot had to reduce gains to damp. Fine tracking was somewhat easier resulting in adequate performance.

ROVER On: Phase 2 evaluation revealed that the ROVER algorithm correctly identified the synchronous inputs as a PIO. However, the evaluation pilot identified the PIO due to seat-of-the-pants cues approximately one half cycle prior to the PIO warning in the HUD. When the evaluation pilot attempted to maintain the phase 2 tracking during a ROVER activation, higher gains resulted in larger stick inputs. Once ROVER cut out, that large input took effect and caused a “secondary” PIO. Phase 3 revealed a slight +/- 10 mil bobble when aggressively tracking the target aircraft, but no sustained oscillations. Did not see the PIO warning during the tracking exercise, nor did the pilot identify a PIO. Bobble resulted in adequate performance.

**Configuration V:** (Case D, 15 deg/sec rate limiting, 0 msec time delay) ROVER Off: Phase 2 resulted in divergent motion and the evaluation pilot elected to come out of the loop. Configuration very sensitive to

pilot aggressiveness. Phase 3 revealed significant lat-dir difficulties. Repositions and subsequent gross acquisitions resulted in a VSS trip in pitch monitor.

ROVER On: Phase 2 resulted in ROVER activations and perceived lack of low frequency control resulting in larger stick inputs. Once ROVER deactivated, the evaluation pilot experienced large pitching motions and entered a secondary PIO. Phase 2 is likely a good evaluation if the goal is for the pilot to remain in the loop during the synchronous input, i.e. ROVER should let the pilot maintain control, just damp the PIO. Phase 2 resulted in VSS trip and PIOR 6 as a default for VSS trips. Evaluation pilot (EP) perceived PIO prior to the PIO warning in the HUD, perhaps one half cycle late. Phase 3 resulted in a VSS (pitch monitor) during the initial gross acquisition. EP attempted using lower gain capture technique which was successful initially. Fine tracking easier, but subsequent reposition resulted in a VSS pitch monitor trip. No PIO warning was observed during this PIO. EP detected PIO; perhaps the data stream should be checked on this test point to make sure that ROVER was indeed activated.

**Configuration C:** (Case C, 15 deg/sec rate limit, 0 msec time delay) ROVER Off: Phase 2 revealed divergent motion. Configuration very sensitive to pilot gain. Immediately sucked into synchronous input which resulted in divergence motion. Phase 3 revealed lat-dir deficiencies. Dutch-roll made tracking difficult until damped out. Fine tracking did not reveal any appreciable longitudinal deficiencies, pilot felt as though desirable performance could be attained, however, on last reposition led to a PIO that forced the pilot to reduce gains.

ROVER On: Similar phase 2 results to the last configuration with ROVER activations precipitating a secondary PIO when the EP attempted to maintain the tracking technique. Phase 3 resulted in fairly stable tracking, but repositions led to PIOs and subsequent VSS pitch monitor trip in Record 14, no PIO warning seen in tape review. Second attempt at this configuration did not result in a VSS trip until a somewhat aggressive reposition forced a significant PIO. ROVER was late in identifying this PIO. The pilot's (EP and safety pilot) were commenting about the lateness of ROVER activation when the EP disengaged the VSS due to uncomfortable negative G forces (cranial-canopy impingement).

**Configuration Z:** (Case C, 30 deg/sec rate limit, 100 msec time delay) ROVER Off: PIO detected in normal control, PIOR 6. Skipped phase 2. Phase 3 revealed somewhat more stable platform under G although constant +- 20 mil limit cycle was present during smooth tracking. EP unable to damp the limit cycle, although motion was not divergent in fine tracking. More aggressive repositions resulted in the EP abandoning the task and coming out of the loop.

ROVER On: Phase 2 revealed similar secondary PIOs to previous configurations. Phase 3 resulted in ROVER activations during the initial turn to capture the target as well as the reversal to align turn circles. ROVER activation was not objectionable in these circumstances and actually aided in maintaining control of the aircraft while maintaining the task. Fine tracking bobble still present, ROVER did not trigger this oscillation. Repositions resulted in PIO and timely ROVER activation, however, maintaining the task with the ROVER algorithm in the loop resulted in higher gain inputs and secondary PIOs similar to previous configurations. Pilot comments revealed that if ROVER activation provided the gain attenuation that pilot strategy would have in the circumstances, then the activation was not objectionable. However, if the gain attenuation was not what the pilot would have done, then the high gain inputs and subsequent secondary PIO would result.

**Configuration J:** (Case C, 45 deg/sec rate limit, 100 msec time delay) ROVER Off: Configuration sensitive to pilot aggressiveness. Phase 2 revealed divergent motion during the synchronous inputs. Phase 3 revealed a lat-dir oscillation that made tracking difficult as well as a longitudinal bobble. Aggressive repositions resulted in PIO that caused the EP to come out of the loop and abandon the task.

ROVER On: Phase 2 results similar to previous configurations. Phase 3 tracking resulted in a long ROVER activation which was very objectionable and forced higher EP gains and eventual secondary PIO. Bobble and lat-dir still during fine tracking, ROVER did not identify as PIO, nor did the EP. However, subsequent repositions resulted in PIO, ROVER activation, EP gain increase and secondary PIO.

**Configuration I:** (Case B, 45 deg/sec rate limit, 100 msec time delay) ROVER Off: Phase 2 revealed limit cycle, no divergence. This behavior is similar to “good” aircraft with objectionable time delay. Phase 3 tracking led to fairly stable tracking with minimal bobble. Desired performance could be attained if the configuration was flown smoothly so as not to induce the bobble. Aggressive repositions excited the bobble but did not result in PIO. CHR 4 due to moderate workload damping the bobble.

ROVER On: Accomplished using the HUD tracking task due to target running out of fuel. Phase 3 revealed that the bobble was more easily induced using the HUD task. ROVER activations did not seem to induce secondary PIO since the error observed at ROVER activation was much smaller than with the live target. Additionally, the task almost seemed to be driving the error smaller during ROVER activation. As a result, EP gains and subsequent stick inputs remained much smaller than with the live target. Coupling between the axis more apparent using the HUD tracking task.

### **Data Flight 7: Pilot 2, 12 Oct 2001**

**Configuration N:** (Case D, 45 deg/sec rate limit, and 0 msec time delay) During phase I the pilot appreciated the nice tracking characteristics. These nice characteristics degraded quite fast as soon as the pilot increased the frequency of his controls’ input. During phase II tracking with ROVER off the pilot experienced a VSS trip due to an AOA monitor. The pilot was impressed no how fast the amplitude of the oscillations grew. During phase II with ROVER engaged the size of the oscillations was noticeably reduced by filter activations and even if the pilot still felt the oscillations to be divergent ROVER managed to keep those bounded. Phase III was characterized by fairly nice fine tracking, but as soon as he intentionally offset and tried a gross acquisition the oscillations tended to grow again. When performing the same task with ROVER activated the size of the oscillations was smaller and a fast reacquisition of the target was easier.

**Configuration L:** (Case C, 30 deg/sec rate limit, and 0 msec time delay) Fairly decent tracking during phase I. As soon as the pilot tried to increase the size of the inputs, he experienced very large oscillations that drove the target out of the HUD field of view and forced the pilot to abandon the task. For this reason he assigned a PIOR of 5. During phase III with ROVER off the pilot noted again the fairly decent tracking configuration’s characteristic during fine tracking. After he intentionally offset from the target and tried to reacquire it as soon as possible he experienced very large oscillations.

During one of the gross acquisitions following intentional offset the aircraft VSS tripped of leading to a PIOR of 6 and CHR of 10. When the ROVER filter was engaged the pilot noted it’s timely intervention resulting in smaller oscillations bounded around the target. During the first gross acquisition of phase III tracking the pilot experienced two ROVER intervention even if he wasn’t experiencing PIO. During the rest of the task ROVER intervention was timely and the oscillations were definitely bounded. The pilot assigned the following ratings for phase III tracking with ROVER on: PIOR 3, CHR 4.

**Configuration O:** (Case B, 45 deg/sec rate limit, and 200 msec time delay) This configuration was characterized by annoying oscillations around target position during all phases of tracking. The oscillations were present as soon as the pilot entered the loop and tried to track the target. During phase II with ROVER off the configuration appeared to be very unstable and prone to divergent oscillations. The pilot several times released controls to retain aircraft control. Exhorted by TM he tried to stay in the loop and this led to rapidly divergent oscillations terminated with a VSS trip. During phase III with ROVER off the pilot experienced the same large oscillations just by entering control loop. The pilot often released controls to prevent the oscillations to grow unbounded. During phase II and III tracking with ROVER on it appeared that the oscillations were still fairly large in amplitude, undamped but bounded by several ROVER interventions. Fine tracking still was almost impossible, even with large pilot compensations.

**Configuration D:** (Case C, 60 deg/sec rate limit, and 0 msec time delay) Very nice configurations. Throughout the all tracking tasks fine tracking was precise and the pipper was almost always very

steady reducing noticeably pilot workload. When the pilot intentionally offset the target position and performed a rapid gross acquisition, the oscillations generated were small and well damped. The pilot made the same comments when the ROVER filter was activated. Due to the nice characteristic of the configuration ROVER activation was almost never required. Couple of times though, it appeared that ROVER activation was a nuisance. This happened during the initial gross acquisition delaying the pilot to get into tracking position even if he wasn't experiencing PIO at all. This led, for phase III tracking with ROVER on to a NR of 3. The pilot thought that was very helpful to have nice configurations alternated with poor ones. This helped him out a lot to "gage" his inputs and make more objective comments.

**Configuration E:** (Case A, 60 deg/sec rate limit, and 200 msec time delay) During phase II tracking with ROVER off, the pilot experienced large oscillations that initially appeared to be divergent. The pilot remained in the loop and surprisingly the oscillations grew fast to large amplitude and sort of stabilized at that amplitude without further increase. During phase III the pilot noted that if he kept small inputs in order to achieve fine tracking, aircraft response was generally predictable and fairly precise. When he intentionally offset to perform gross acquisitions again, the aircraft produced the same kind of oscillations previously described. When ROVER was selected on, the pilot noted, upon filter activation that the oscillations were damped very fast keeping the pipper fairly close to target positions. The ROVER activations were generally pretty timely, but throughout all the tracking tasks large pilot compensations were required in order to keep control inputs fairly small.

**Configuration G:** (Case C, 60 deg/sec rate limit, and 200 msec time delay) Very poor configuration. With ROVER off, both during phase I and II the pilot experienced very large, divergent oscillations. In both cases the tracking task was terminated by a VSS trip. When ROVER was selected on the pilot noted some minor improvements. The divergent oscillations could be stopped by releasing controls as soon as the filter kicked in. When the pilot decided to stay in the loop and kept low frequency inputs ROVER initially kept the oscillations bounded but as soon as it faded out the aircraft motion became divergent in the order of two seconds. The pilot comment was that "it appears that the fight is too big for ROVER".

### **Data Flight 8: Pilot 1, 15 Oct 2001**

**Configuration V:** (Case D, 15 deg/sec, and 0 msec delay). Phase 2 task resulted in rapid pitch divergence and VSS trip. Phase 3, tracking was "not too bad" but any big input to follow a large target move resulted in a large overshoot and a VSS trip. Phase 2 ROVER on had a pitch monitor VSS trip after control given back from a ROVER activation with large stick input still applied. ROVER arrested the initial PIO but attempting to continue the tracking task with stick inputs resulted in a pitch monitor VSS trip as control was given back. Phase 3 ROVER on resulted in a complete task with no VSS trip. ROVER arrested the initial PIO in a "timely" activation but still got a "big oscillation" attempting to continue the tracking task as ROVER disengaged.

**Configuration U:** (Case B, 45 deg/sec, and 0 msec delay). Phase 1 and 2 fine tracking was "OK" but it was an "uncomfortable" configuration with a bounded non-divergent oscillation. Phase 3 it was "tough" to get it to settle down into fine tracking after a big input for gross acquisition. Phase 2 ROVER on, got activation on initial motion before any oscillations, almost a nuisance rating 3. Seemed to be holding on too long. Phase 3 ROVER on got an activation on a large input, this was "timely" as aircraft was felt to be "digging in". At disengagement was left in a good position to "settle down into fine tracking". Still had an annoying bobble around the target during fine tracking.

**Configuration I:** (Case B, 45 deg/sec, and 100 msec delay). Felt like a "light" aircraft. Phase 2 was divergent, stopped before a VSS trip. Phase 3 on big inputs had to be "careful modulating inputs" to prevent divergence, but not backing out of the loop completely. Phase 2 ROVER on was "weird"! Activation of ROVER was timely, but attempting to continue control inputs during ROVER activation resulted in large oscillations as ROVER disengaged as there were large control inputs left in. Got a

PIO in the opposite direction, ROVER was “making the difficult”. Phase 3 it felt like ROVER was not giving the pilot the low pass inputs that were desired when ROVER was active, “can’t pull the nose back to where I want it”.

**Configuration F:** (Case C, 60 deg/sec, and 100 msec delay). Phase 2 was definitely diverging, backed out before VSS trip. Phase 3 the pilot had to back out of the loop to get the aircraft to settle and track. If the pilot stayed in the loop “it would bounce around” all day. The workload was intolerable. Phase 2 ROVER on resulted in the pilot “getting out of phase with ROVER”. “I was crossing the target after ROVER came off, and making it come back on again” attempting to continue the phase 2. This was a secondary PIO case. Phase 3 there were numerous ROVER activations but the pilot felt “like I’m fighting them”. The pilot was “having to be very fine with stick inputs to get any tracking” but was not backing out of the loop. ROVER did not improve the task scores but did achieve a lowering of the workload in the CHR.

**Configuration K:** (Case C, 45 deg/sec, and 200 msec delay). The configuration was “light” and the pilot had trouble tracking even in phase 1. Phase 2 resulted in a very quick VSS pitch monitor trip. Phase 3 the VSS tripped right away, “it’s a mess”. Phase 2 ROVER on violent oscillations were still encountered although it was felt that ROVER was helping retain control. Phase 3 resulted in a VSS trip, however, ROVER kept control for longer than the ROVER off case but no tracking was possible.

**Configuration T:** (Case B, 60 deg/sec, and 0 msec delay). Felt like a “much slower initial response” than the previous configuration. Only a small bounded oscillation was experienced with large full deflection inputs. Phase 3 was able to achieve fine tracking fairly quickly even after large inputs. Phase 2 ROVER on, the pilot was able to get to large inputs before ROVER engaged. Still experienced bounded oscillations. However, the pilot commented “didn’t feel like I was able to control the aircraft with ROVER on” and that he was “disconnected”. Phase 3 there was only one activation of ROVER on a large gross acquisition input, and when it switched off “it left me in a good position for tracking”. Ratings were similar for both ROVER on and off.

**Configuration Y:** (Case B, 60 deg/sec, and 100 msec delay). Felt “sensitive”, phase 1 fine tracking was “reasonable”. Phase 2 the aircraft diverged with large inputs and the VSS tripped. Phase 3 the pilot had to back out of the loop to get a tracking solution otherwise felt that he was “driving oscillations” about the target. Phase 2 ROVER on, ROVER activations were “timely” but it seemed to remain engaged for “ages”. Attempting to continue low bandwidth tracking resulted in large stick inputs being present when ROVER disengaged resulting in a subsequent PIO. The pilot felt that the aircraft response was “stepped”. During phase 3 ROVER on, ROVER activations were “timely” and it seemed to not stay on as long as it did during phase 2. When it disengaged it left the pilot “in a good spot for tracking”. ROVER did a good job at preventing oscillations.

## **Data Flight 9: Pilot 3, 16 Oct 2001**

**Configuration E:** During E (Case A, 60 deg/sec, and 200 msec delay), the target aircraft performed a 2G-turn for phase 2 maneuvers and a 2-3G-turn for the phase 3 task. The pilot observed oscillations that slowly grew in amplitude to a endgame bounded oscillation of nearly +/- 50 mils. The fine tracking of phase 3 revealed undesirable bubbles of +/- 10 mils and +/- 25 mil oscillations during gross acquisition. This resulted in a CHR of 8 and a PIOR of 5 for both phase 2 and phase 3 tasks.

ROVER engaged several times during the next phase 2 task. “The ‘PIO’ activations kept the oscillations to within nearly 20 mils.” There were a couple of timely activations for large inputs as well as small amplitude/small input maneuvering – PIOR of 3. Performance did not improve during phase 3 tracking as ROVER only engaged on the gross acquisition/large pulls. The configuration was “very difficult” as multiple bubbles prevented the pilot from achieving adequate performance – CHR 8 and PIOR 5.

**Configuration D:** During D (Case C, 60 deg/sec, and 0 msec delay), the pilot commented that the aircraft was smooth and generally presented few undesirable overshoots or oscillations during phase 2 or phase 3 tasks. The aggressive pulls/repositions during phase 3 were responsive and the pilot commented, “I would not have wanted any ROVER activations during this tracking” – CHR 3 and PIOR 2.

ROVER did activate several times during the phase 2 task – all were considered a nuisance – NR of 3 and PIOR 3. During the phase 3 task, the pilot experienced a slight roll PIO that degraded tracking performance. “There was a flash of “PIO” during gross acquisition as the aircraft oscillated while I pulled the pipper to the target.” This activation was also deemed a nuisance, but the duration of the filter did not significantly degrade the tracking performance – CHR 5 and PIOR 3 (primarily due to the lateral PIO). Because there were not ROVER activations during the fine tracking, this is not considered a good comparison data point.

**Configuration J:** During J (Case C, 45 deg/sec, and 100 msec delay), the pilot experienced a highly oscillatory, very PIO-prone aircraft. “Oh Boy! This is very touchy!” The phase 2 task was terminated prior to a VSS trip while observing a divergent PIO – PIOR of 6. Phase 3 displayed some undesirable motion on large inputs –“all kind of undesirable motion on gross acquisition – pitch and roll.” The aircraft experienced some bubbles during fine tracking but diverged during one large input resulting in a pitch monitor VSS trip – PIOR of 6 and CHR of 10.

During the ROVER active phase 2 maneuvering, ROVER did activate several times and generally kept the oscillation to within +/- 25 mils. These activations were called “timely”; however, one large stick input as ROVER disengaged forced a pitch monitor safety trip. ROVER performed well during the phase 3 task as large overshoots were kept bounded within +/- 25 mils. ROVER was driven to engage by significant overshoots during gross acquisition. Fine tracking had undesirable pitch motion of +/- 15 mils. “Large inputs on gross acquisition were followed by timely ROVER activations and several events.” The huge overshoots (+/- 60 mils) seen during the ROVER disengaged trials were suppressed by the ROVER algorithm.

**Configuration N:** During N (Case D, 45 deg/sec, and 0 msec delay), the pilot observed a very slowly growing divergent oscillation and manually terminated the task – PIOR of 5. The first 2 phase 3 tasks were interrupted by nuisance safety trips. Record 16 was a good task in which the pilot experienced significant bubbles of +/- 15 mils but was able to achieve adequate performance. The oscillations did not feel “PIO(ish)” – CHR 6 and PIOR of 3.

The ROVER active phase 2 resulted in several early ROVER activations and some undesirable motion. ROVER engaged during an apparent bounded oscillation of +/- 20 mils – PIOR of 3. After a nuisance AOA trip of the first phase 3 task, the pilot observed timely “PIO” during gross acquisition followed by an early activation during fine tracking. There were “small bubbles in pitch and roll but none were worthy of ROVER.” A PIOR of 2, CHR of 5 and NR of 3 were assigned.

**Configuration F:** During F (Case C, 60 deg/sec, and 100 msec delay), the aircraft “felt PIO susceptible” and displayed divergent oscillations during phase 2 maneuvering – PIOR of 6. Phase 3 tracking highlighted “very undesirable fine tracking pitch bubbles – bigger than previous configurations.” Gross acquisition had multiple overshoots of 25-40 mils with multiple bounded oscillations of +/- 20 mils. The pilot was not able to achieve adequate performance – PIOR 5 and CHR of 8.

ROVER engaged phase 2 maneuvering exhibited timely activations and left small errors in tracking when ROVER disengaged. +/- 30 mil overshoots drove “PIO” activations – all oscillations were bounded by ROVER activations – PIOR of 3. The phase 3 tracking produced the following comment, “Best performance by ROVER so far. Activations in gross acquisition and occasionally during fine tracking – all appeared timely.” ROVER kept oscillations within +/- 20 mils. “The tighter I get in the loop, the larger the oscillations get.” This tight control was followed directly by ROVER activations and a slight improvement in tracking performance – PIOR of 3 and CHR of 6. While the ROVER-

active configuration displayed slightly less undesirable pitch motion during fine tracking, it was still not a very good air-to-air tracking aircraft configuration.

**Configuration Z:** For Z (Case C, 30 deg/sec, and 100 msec delay), only the ROVER off events were accomplished due to target fuel. The phase 2 maneuvering highlighted a sensitive configuration that appeared PIO prone. “Fingertip control was required for gentle maneuvering.” The aircraft quickly transitioned to a divergent oscillation. The pilot terminated the task prior to a VSS trip – PIOR of 6. After on nuisance AOA trip during the phase 3 tracking, the pilot completed the task with multiple significant oscillations were ROVER would have been requested. Fine tracking was difficult with pitch bobbles of +/- 10 mils. Large acquisitions drove large overshoots. One in particular resulted in 4 large overshoots of the target aircraft – each approximately +/- 35 mils. ROVER would certainly have been appreciated during that task.

**Configuration W:** During W (Case A, 60 deg/sec, and 100 msec delay), the HUD task was flown as the target had already left the airspace. The pilot manually terminated the phase 2 task after experiencing significant overshoots – PIOR 5. Phase 3 tracking showed significantly undesirable bobbles of 5-10 mils. “Gross acquisition was pretty good, but fine tracking was difficult.” No true PIO was experienced – PIOR 3 and CHR of 5.

The pilot manually terminated the phase 2 task after experiencing several timely ROVER activations. The first engagement occurred after a 20-mil overshoot – all engagements generally kept the pipper within 30 mils of the target. The phase 3 task was a mix of both timely and early ROVER activations. “The main problem was the pitch bobbles and ROVER did not help prevent/suppress those.” Events during this task were for timely activations. Good video of phase 2 exists at 1+12 on the HUD tape. No significant task performance was experienced due to no ROVER activations during the fine tracking.

### **Data Flight 10: Pilot 1, 16 Oct 2001**

**Configuration H:** (Case C, 45 deg/sec, and 0 msec delay). Phase 1 and 2 only generated small oscillations even with large inputs. Phase 3 there were 2 or 3 oscillations after a large input for it to settle down, then fine tracking was reasonable. Didn’t feel need for ROVER. Phase 2 ROVER on oscillations were small when ROVER activated making it seem early, although the stick inputs were large at that point. Phase 3 ROVER on didn’t see any engagements. Little pitch bobbles after large inputs but didn’t feel need for ROVER.

**Configuration G:** (Case C, 60 deg/sec, and 200 msec delay). Felt “very sensitive”. Oscillations building just trying to track in phase 1 and 2, as soon as attempted to drive phase 2 had a VSS pitch monitor trip. Very easy to drive to PIO. Phase 3 hard to stop oscillations when in the loop, very sensitive. Easily went into divergent PIO after gross acquisition resulting in VSS trip. Phase 1 and 2 ROVER on made control of aircraft better but still very difficult to keep on target in phase 2. Mannequin effect seems to be generating oscillations. Phase 3 ROVER on, ROVER engaged on initial acquisition maneuver and on numerous times after that. ROVER allowed the aircraft to be kept under control i.e. not divergent, but it was impossible to track as ROVER was on so often.

**Configuration V:** (Case D, 15 deg/sec, and 0 msec delay). Fine tracking felt responsive in Phase 1. In phase 2 the aircraft lagged what I was wanting and demanding with bigger inputs resulting in divergent oscillation and a VSS trip. Phase 3 initial fine tracking was good, but an abrupt gross acquisition from lag caused an oscillation that diverged rapidly on the 3<sup>rd</sup> oscillation resulting in a VSS trip. Phase 2 ROVER on, diverged with relatively small inputs, VSS tripped before any ROVER engagements. ROVER would have been desirable, nuisance rating 1. Phase 3 ROVER on, overshoot on a gross acquisition from lag resulted in divergence and a VSS trip almost as soon as ROVER activated. An earlier activation of ROVER would have helped here.

**Configuration F:** (Case C, 60 deg/sec, and 100 msec delay). Phase 2 initially appeared to be giving bounded oscillations, but it slowly diverged with increasing inputs eventually reaching a VSS pitch monitor trip. Phase 3 gross acquisitions caused a controllable oscillation that required “working very hard” to settle down the tracking. Phase 2 ROVER on with large inputs ROVER did a “good job” at keeping the pilot pointed at the target. What was left was “merely undesirable motions”. Phase 3 ROVER on ROVER engaged on the initial maneuver and helped achieve a tracking solution. After that ROVER engaged on large input excursions but not on smaller oscillations about the target. The configuration was still hard to settle down in fine tracking. ROVER “did not help as much as I thought it would from phase 2”.

**Configuration M:** (Case D, 60 deg/sec, and 0 msec delay). Hard to drive oscillations in phase 2, definitely bounded. Phase 3 fine tracking was “fairly steady”, just undesirable motions on the gross acquisitions. Phase 2 ROVER on, ROVER activated after first 2 or 3 inputs when the oscillations were still small which seemed a bit early. It would then disengage quickly resulting in a “jerky” response. Phase 3 ROVER on, only had a quick flash of ROVER engaging, didn’t seem to affect the tracking solution.

### **Data Flight 11: Pilot 1, 17 Oct 2001**

**Configuration W:** (Case A, 60 deg/sec, and 100 msec delay). Phase 1 exhibited good characteristics with good fine tracking. Phase 2 was slightly divergent with aggressive inputs but eventually reached a large bounded oscillation. Phase 2 ROVER on, ROVER did a good job at bounding/stopping oscillation but still had undesirable motions. If stick inputs were held in during ROVER engagement, ROVER stayed on a long time and there were abrupt motions as ROVER disengaged. If stick inputs were released when ROVER activated, ROVER appeared to stay on for a shorter time and it was smoother as ROVER disengaged. Phase 3 ROVER on, ROVER generally activated after about 2 oscillations and when it disengaged “it left me near the target for tracking”. Stick inputs were held during ROVER engagement but they weren’t full displacement so the transients as ROVER disengaged were minor.

**Configuration O:** (Case B, 45 deg/sec, and 200 msec delay). Felt very “light”. Got considerable oscillations even in phase 1. Phase 2 was divergent. Phase 3 was very oscillation prone on gross acquisition and it was necessary to back out of the loop to try and achieve any fine tracking at all. Phase 2 ROVER on, Rover engaged for big inputs on approximately the second oscillations and stayed on for what seemed like a long time, but at disengagement left the pilot in a good tracking position. Phase 3 ROVER on, ROVER engaged on initial acquisition maneuver before any oscillations which seemed early, after that it engaged in a timely manner on oscillations and helped to get back to a tracking position although there were still numerous small bobbles about the target.

**Configuration H:** (Case C, 45 deg/sec, and 0 msec delay). Tracking was not as sensitive as the last configuration. Phase 2 resulted in some aggressive oscillations that were uncomfortable but they were bounded. Phase 3 fine tracking was “precise, easy”, gross acquisition would result in a couple of small bounded oscillations about the target. Phase 2 ROVER on, it was felt that ROVER did a “good job”, engaging either on the initial motion or a couple of oscillations. Phase 3 ROVER on, had to be aggressive to get ROVER to engage. ROVER engaged after one overshoot and brought the pilot “halfway back to the target” from where it was straightforward to work back to a tracking solution.

**Configuration L:** (Case C, 30 deg/sec, and 0 msec delay). Phase 1 fine tracking “wasn’t bad” with a small oscillation about the target. However, phase 2 was quickly divergent leading to a VSS trip. Phase 3 with gross acquisition there were some small oscillations but the pilot felt that overall it was more undesirable motions than oscillations. Phase 2 ROVER on, ROVER “worked well”. It would engage early in the oscillation and there was “no stepping” when it disengaged even with continued stick input. Phase 3 ROVER on, on the initial pull to the target ROVER engaged briefly, this wasn’t

considered necessary by the pilot but it didn't seem to hinder or slow the aircraft response. There were still small oscillations in fine tracking which ROVER didn't activate for, a large input was required to get ROVER to activate, generally after a couple of oscillations.

**Configuration X:** (Case C, 30 deg/sec, and 200 msec delay). A very "sensitive" configuration. Phase 2 lead very quickly to a divergent oscillation. Phase 3 the aircraft was very sensitive and every big input lead to a big oscillation requiring the pilot to back out of the loop to retain aircraft control. Continual small oscillations about the target when attempting fine tracking. Phase 1 ROVER on felt "twitchy", phase 2 resulted in a VSS trip on the second oscillation. ROVER engaged just before the VSS trip. Phase 3 ROVER on, ROVER was doing a "good job" for large oscillations with controllable disengagements showing "no stepping". It was still easy to drive small oscillations about the target during fine tracking which were below the ROVER threshold. Only on instance where the pilot wanted ROVER but didn't get it, nuisance rating 1.

**Configuration A:** (Case B, 30 deg/sec, and 100 msec delay). Phase 2 the VSS tripped, however, the oscillations felt bounded and it would have been a PIOR 5 if the VSS hadn't tripped. Phase 3 it was "easy to drive an oscillation off gross acquisition" although it wasn't felt that ROVER was required. Fine tracking was OK when it had settled down. Phase 2 ROVER on, ROVER engaged on numerous occasions. If control inputs were removed when ROVER was activated, ROVER disengaged quickly and "left me close to the target" with no transient motions. If control inputs were held during ROVER engagement ROVER seemed to stay on longer and leave the pilot "further away from the target" with a "stepping" motion as it disengaged. Phase 3 ROVER on, control inputs were left in during ROVER engagement which resulted in ROVER "working very nicely" with comments similar to those for phase 2 ROVER on. Fine tracking was still difficult and resulted in a CHR 5 even though desired tracking was achieved.

### **Data Flight 12: Pilot 2, 17 Oct 2001**

**Configuration W:** (Case A, 60 deg/sec rate limit, and 100 msec time delay) This configuration had fairly nice tracking characteristics either with ROVER on or off. During phase II tracking with ROVER off the pilot didn't notice any undesirable motions. The oscillations induced by large phase II inputs were generally of small amplitude and well damped. When the filter was switched on the previously mentioned oscillations were even smaller due to ROVER activation and the tracking piper was always pretty close to the target. Phase III tracking led to desired performances in both cases and when ROVER was switched on the pilot noted its activation only once and for less than a second.

**Configuration F:** (Case C, 60 deg/sec rate limit, and 100 msec time delay) phase II tracking was characterized, with both ROVER on and off, by a pitch monitor VSS trip. This was mainly due to the fast speed at which the oscillations grew. Fine tracking was generally nice but as soon as the pilot initiated large amplitude control inputs in order to assiduously tracking the target the aircraft's oscillations diverged rapidly. During phase III with ROVER on the pilot experienced timely ROVER activations that kept the oscillations bounded and the piper fairly close to the target. As expected fine tracking characteristics were fairly good.

**Configuration T:** (Case B, 60 deg/sec rate limit, and 0 msec time delay) Overall a very nice configuration. The aircraft appeared in all tracking tasks very stable. It was very easy to make precise corrections and aircraft response was always predictable, even with intentionally large control inputs. During phase II with ROVER switched on the pilot noted several ROVER activations even if he was experiencing any PIO at all. These filter interventions often resulted in an increase in pilot workload. During phase III tracking with ROVER on the pilot never experienced PIO and ROVER agreed by never kicking in.

**Configuration K:** (Case C, 45 deg/sec rate limit, and 200 msec time delay) poor handling qualities in all the tracking tasks performed characterized This configuration. The pilot always noted the presence of a large bubble that made fine tracking almost impossible. As soon as the pilot slightly increased the amplitude of the inputs he experienced divergent oscillations that led to a VSS trip due to a divergent pitch monitor. During phase III with ROVER off the extensive pilot compensations were required to maintain aircraft control. The pilot had to abandon the task several time. Phase II with ROVER on was characterized by two different aircraft behavior. If the pilot abandoned the task by releasing control upon ROVER activations the oscillations would immediately cease and the tracking pipper remained pretty close to the target. When the pilot remained in the loop the oscillations became undamped and divergent leading to a VSS trip, phase III with ROVER on had the same characteristics previously explained with ROVER off. The pilot never saw the filter activation throughout the all tracking task. He often released the controls and got out of the loop in order to keep the aircraft from departing.

**Configuration U:** (Case B, 45 deg/sec rate limit, and 0 msec time delay) Overall a very nice configuration. The aircraft appeared in all tracking tasks very stable. It was very easy to make precise corrections and aircraft response was always predictable, the pilot never experienced any residual oscillations following large gross inputs. During phase II with ROVER switched on the pilot noted several ROVER activations even if he was experiencing any PIO at all. These filter interventions often resulted in an increase in pilot workload by taking the pilot off the controls even if it wasn't required. During phase III tracking with ROVER on the pilot never experienced PIO and ROVER agreed by never kicking in.

**Configuration X:** (Case C, 30 deg/sec rate limit, and 200 msec time delay) During phase II tracking the pilot experienced a VSS trip. This happened with both ROVER on and off. When ROVER was on the aircraft departed and the pilot never saw ROVER activation. The presence of a large bubble made fine tracking almost impossible and more than 80% of pilot's brain bytes were devolved in aircraft control. The tracking task was often abandoned due to the necessity of releasing controls to prevent departure. Phase III tracking with ROVER on brought the benefit of the fact that aircraft controllability was never in question. Besides this tracking characteristics were still very poor and still large pilot compensations were required throughout the all task.

**Configuration A:** (Case B, 30 deg/sec rate limit, and 100 msec time delay) This configuration was characterized by a moderate annoying bubble of approximately 10 mrad around target position during gentle tracking. During phase II tracking with ROVER off the pilot experienced pretty large oscillations that initially grew kind of fast but then stabilized quite soon. These large oscillations were bounded but not damped. To damp those out the pilot had to back off and release the controls. During phase II with ROVER on the pilot experienced several timely ROVER activations which kept the amplitude of oscillations definitely smaller. During phase III the pilot saw ROVER activation only once and prevented a large overshoot during gross acquisition. It appeared that ROVER couldn't do anything to reduce the previously described bubble experienced during fine tracking.

Table C-2. Instrumentation Parameters

No	Parameter Name	Description	Comments	Veridian Parameter Name
1	de_cmd	Elevator command from the pilot (before ROVER)	The source of this signal is the pilot output just before it is imputed into the ROVER block	TMP.DEC
2	mod_de_cmd	Elevator command after the ROVER block	The source of this signal is the elevator deflection command after it has passed the ROVER block	ROV_DE_CM_D
3	de_cmd_filtered	Elevator command after the notch	The source of this signal is the elevator deflection command after the notch filter (before the switch that decides which source to take)	DECMD_FILT
4	Act_in	Input to the model actuator	The source of this signal is the elevator deflection command just before the actuator (in the model A/C, just before the airframe model)	TMP.ACT
5	Act_out	output from the model actuator	The source of this signal is the elevator deflection just after the actuator (in the model A/C, just before the airframe model)	TMP.QDOTM
6	Act_in_rate	Rate Input to the model actuator	The source of this signal is the elevator rate command just before the actuator (in the model A/C, just before the airframe model)	TMP.ACT_RT
7	Act_in_rate	Rate output from the model actuator	The source of this signal is the elevator rate just after the actuator (in the model A/C, just before the airframe model)	TMP.QDOTRT
8	Act_rate_flag	Model rate limit flag	Flag if the actuator rate limit was reached	TMP.RLFLAG
9	Rover_value	Rover value (0-4)	The source of this signal is the Rover block. This value tells us how close are we to PIO (when all criteria are met Rover_value=4)	ROVR_VALUE
10	Rover Activation Switch	Position of the rover activation switch	When this parameter is 1 the system will pass the filtered pilot command if Rover=4	ROVR_ACTIV
11	Condition PR	The value of the pitch rate condition	This parameter equals 1 if the pitch rate threshold is exceeded	RVR_CONDS (combined parameters into HEX word)
12	Condition ED	The value of the Elevator command condition	This parameter equals 1 if the Elevator command threshold is exceeded	RVR_CONDS (combined parameters into HEX word)

No	Parameter Name	Description	Comments	Veridian Parameter Name
13	Condition PA	The value of the phase angle condition	This parameter equals 1 if the phase angle threshold is exceeded	RVR_CONDS (combined parameters into HEX word)
14	Condition qf	The value of the frequency condition	This parameter equals 1 if the frequency is in the PIO range	RVR_CONDS (combined parameters into HEX word)
15	q_diff	Pitch rate amplitude	q_max-q_min (from the ROVER block)	RVR_PR_DIF
16	de_diff	Commanded elevator amplitude	de_max-de_min (from the ROVER block)	RVR_DE_DIF
17	angle_diff	Phase angle (q and de)	Phase angle difference between q and de	RVR_PA_DIF
18	q_fre	Pitch rate frequency	Pitch rate frequency from the ROVER block, measured between pitch rate min and max	ROVR_QFREQ
19	AC_AOA	Real VISTA A/C Angle of attack	The source for this signal is the Real VISTA AOA	ALPHA_CF
20	AC_q	Real VISTA A/C pitch rate	The source for this signal is the Real VISTA pitch rate	Q
21	AC_p	Real VISTA A/C roll rate	The source for this signal is the Real VISTA roll rate	P
22	AC_r	Real VISTA A/C yaw rate	The source for this signal is the Real VISTA yaw rate	R1
23	AC_theta	Real VISTA A/C pitch angle	The source for this signal is the Real VISTA pitch angle	INS_PITCH
24	AC_Phi	Real VISTA A/C roll angle	The source for this signal is the Real VISTA roll angle	INS_ROLL
25	AC_heading	Real VISTA A/C heading	The source for this signal is the Real VISTA heading	INS_TDHG
26	AC_Vt	Real VISTA A/C true airspeed	The source for this signal is the Real VISTA true airspeed	
27	AC_Vc	Real VISTA A/C calibrated airspeed	The source for this signal is the Real VISTA calibrated airspeed	VCAS

28	AC_M	Real VISTA A/C Mach	The source for this signal is the Real VISTA Mach	MACH
----	------	---------------------------	--	------

No	Parameter Name	Description	Comments	Veridian Parameter Name
29	AC_Nz	Real VISTA A/C load factor	The source for this signal is the Real VISTA load factor	NZP
30	AC_Alt	Real VISTA A/C altitude	The source for this signal is the Real VISTA altitude	HP
31	Configuration	The simulated A/C configuration in the VSS	Which A/C is being simulated now –A,B,C,D / Rate limit / Time delay / Stick	VSS_CONF IG
32	HUD_TR_P_Err	HUD tracking task pitch error	HUD tracking task pitch error calculation	TT.P_ERR
33	Hud_TR_R_Error	HUD tracking task Roll error	HUD tracking task roll error calculation	TT.R_ERR
34	Hud_TR_T_Error	HUD tracking task total error	HUD tracking task total error calculation	Ground calculation
35	Hud_TR_D_Score	HUD tracking task desired score	HUD tracking task desired score (total average of the task – the number presented in the HUD at the end of the task)	TT.D_SCORE
36	Hud_TR_A_Score	HUD tracking task adequate score	HUD tracking task adequate score (total average of the task – the number presented in the HUD at the end of the task)	TT.A_SCORE
37	RDR_EL_Error	Radar lock pitch tracking error	The pitch tracking error from the radar lock	FCR_EL_Error
38	RDR_AZ_Error	Radar lock AZ tracking error	The azimuth tracking error from the radar lock	FCR_AZ_Error
39	RDR_To_Error	Radar lock total tracking error	The radar RMS error	FCR_RMS_Error
40	C_LN_SF	Center Long stick force	Center Long stick force from the VSS system	FECS1
41	C_LN_SD	Center Long stick deflection	Center Long stick deflection from the VSS system	DECS1
42	S_LN_SF	Side Long stick force	Side Long stick force from the VSS system	FESS1
43	S_LN_SD	Side Long stick deflection	Side Long stick deflection from the VSS system	DESS1
44	C_LT_SF	Center Lat stick force	Center Lat stick force from the VSS system	FACS1

45	C_LT_SD	Center Lat stick deflection	Center Lat stick deflection from the VSS system	DACS1
No	Parameter Name	<i>Description</i>	<i>Comments</i>	Veridian Parameter Name
46	S_LT_SF	Side Lat stick force	Side Lat stick force from the VSS system	FASS1
47	S_LT_SD	Side Lat stick deflection	Side Lat stick deflection from the VSS system	DASS1
48	Total Fuel	Total Fuel	Total A/C fuel for mission control	FUELTOT
49	Record number	Last record used	Record number to synchronize for the data reduction	Record Number (display as HEX number)
50	VSS engage	VSS engage flag	A flag that shows if the VSS is engaged or not or if safety trips were activated	VSS_MOD_E
51	Pilot Event stick	Pinky button	Stick event button	VRS_COD_E
52	Pilot Event throttle	IFF	Throttle event button	VRS_COD_E

**Notes:**

- 1) Due to the fact that TM is not required for any of the evaluation sorties, none of the above parameters is a go/no-go requirement for the TM room.
- 2) All the critical parameters are internal to the VSS; therefore, if the VSS is operating normally, all of the VSS parameters will be available for post processing.
- 3) The above list does not contain any no-go parameters.

## Bibliography

A'Harrah, Ralph C. An Alternate Control Scheme for Alleviating Aircraft-Pilot Coupling. AIAA-94-3673-CP. NASA Headquarters, Washington DC, March 1994.

Anderson, Mark R. and Anthony B. Page. Unified Pilot-Induced Oscillation Theory, Volume III: PIO Analysis Using Multivariable Methods, Final Report. Contract No. F33615-94-C-3611, WL-TR-96-3030. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Ashkenas, I.L., H.R. Jex, and D.T. McRuer. Pilot-Induced Oscillations: Their Cause and Analysis. NORAIR Report No. NOR-64-143, Northrop Corporation, June 1964.

Bailey, R. and R. Smith, An In-Flight Investigation of Pilot-Induced Oscillation Suppression Filters During the Fighter Approach and Landing Task. Calspan Report No. 6645-F-9, Contract No. F33615-79-C-3618, October 1981.

Bjorkman, E., R. Bennett, D. Eidsaune, S. Miyamoto, and O. Wilkinson. NT-33 Pilot Induced Oscillation Prediction Evaluation, Final Report, USAFTPS-TR-85B-S4, Edwards AFB CA, June 1986.

Buckley, J., K. Citrus, J. Hodgkinson, R. Hoh, D. Mitchell, and J. Preston. Unified Pilot-Induced Oscillation Theory, Volume II: Pilot Induced Oscillation Criteria Applied to Several McDonnell Douglas Aircraft, Final Report. Contract No. F33615-94-C-3612. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Calspan Corporation, Advanced Technology Center. Development of Quantitative Design Criteria for Identification of Pilot-Induced Oscillation Tendencies. Calspan Proposal No. 0442, June 1993.

Chapa, Michael J. A Nonlinear Pre-filter to Prevent Departure and/or Pilot-Induced Oscillations (PIO) due to Actuator Rate Limiting. MS thesis, AFIT/GAE/ENY/99M-01. School of Aeronautical Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1999 (AD-A361655).

Chapa, M., E. Fick, D. Kraabel, M. LeTourneau, and T. Parker. Results of Attempts to Prevent Departure and/or Pilot-Induced Oscillations (PIO) Due to Actuator Rate Limiting in Highly Augmented Fighter Flight Control Systems, Final Report, AFFTC-TR-98-26, Edwards AFB CA, December 1998.

## Bibliography (cont.)

Cox, C., C. Lewis, J. Clark, and R. Pap. Neural Network Compensation Strategy for Preventing Pilot Induced Oscillations. Contract No. F33615-95-C-2540, Accurate Automation Corporation, Chattanooga TN, November 1995.

Cox, C., L. Carlton, D. Donovan, B. Duncan, B. Hall, P. Mays, R. Pap, T. Robinson, and R. Saeks. Neural Network Compensation Strategy for Preventing Pilot Induced Oscillations. Contract No. F33615-96-C-3608, Accurate Automation Corporation, Chattanooga, TN September 1999.

High Plains Engineering. Effects of Artificial Feel System and Flight Control System Gain On Handling Qualities and PIO Susceptibility. Tehachapi CA, May 1993.

Hodgkinson, John. Aircraft Handling Qualities. Restin VA: AIAA, 1999.

Johnson, D., D. Ballance, M Maurizio, P. Cali, V. Shaferman, R. Bailey. A Limited Evaluation of a Pilot-Induced Oscillation Suppression Algorithm – Project HAVE ROVER, Test Plan, TPS-TP-01A-04, Edwards AFB CA, 26 September 2001.

Johnson, D., D. Ballance, M Maurizio, P. Cali, V. Shaferman, R. Bailey. A Limited Evaluation of a Pilot-Induced Oscillation Suppression Algorithm – Project HAVE ROVER, Technical Information Memorandum, AFFTC-TIM-01-10, Edwards AFB CA, December 2001.

Kish, Brian A. A Limited Flight Test Evaluation of Pilot Induced Oscillation due to Elevator Rate Limiting (HAVE LIMITS). AFFTC-TR-97-12, August 1997.

Klyde, David H., Duane T. McRuer, and Thomas T. Myers. Unified Pilot-Induced Oscillation Theory, Volume I: PIO Analysis With Linear and Nonlinear Effective Vehicle Characteristics, Including Rate Limiting, Final Report. Contract No. F33615-94-C-3613, WL-TR-96-3028. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Liebst, Brad S. "Pilot-Induced Oscillations (PIO): Causes and Corrections," Proceedings of the Japan Society for Aeronautical and Space Sciences 13<sup>th</sup> International Session of the 37<sup>th</sup> Aircraft Symposium, Tokyo Japan, 13-15 October 1999.

Leggett, David B., Flying Qualities Engineer, Air Vehicles Division, Air Force Research Laboratory, Wright-Patterson AFB OH. Personal Interviews. August-October 2000.

## Bibliography (cont.)

Leggett, David B. "On-Board PIO Detection/Prevention." Presentation at the PIO Workshop, NASA Dryden, 6-8 April 1999.

Markofski, Andrew R. Senior Research Engineer, Veridian Engineering, Flight Research Group. Buffalo, NY. Interviews. November 1999 through December 2001.

MATLAB® & Simulink®. Versions 5.1 and 3.0. Computer Software. The Mathworks, Inc., Natick MA, 1997.

McKay, K. Summary of an Agard Workshop on Pilot Induced Oscillation. British Aerospace Defense (Military Aircraft Division), United Kingdom. AIAA-94-3668-CP.

McRuer, Duane T. (Committee Chair), National Research Council. Aviation Safety and Pilot Control. National Academy Press. Washington DC, 1997.

Military Standard, Flying Qualities of Piloted Aircraft. MIL-HDBK 1797A, Department of Defense, January 1990.

Mitchell, David G. and Roger H. Hoh. Development of a Unified Method to Predict Tendencies for Pilot-Induced Oscillations. WL-TR-95-3049, Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, June 1995.

Mitchell, David G. and Roger H. Hoh. The Measurement and Prediction of Pilot-in-the-Loop Oscillations. AIAA-94-3670-CP. Hoh Aeronautics, Inc. Lomita CA, August 1994.

Mitchell, David G. Technical Director, Hoh Aeronautics, Inc. Lomita CA. Telephone Interviews. August 1999 through December 2001.

Moorhouse, David J. Experience with the R. Smith PIO Criterion on the F-15 STOL & Maneuver Technology Demonstrator. AIAA-94-3671-CP.

Nguyen, Ba T. and Thomas J. Cord. Comparison and Analysis of Pilot-Induced Oscillation Characteristics from Flight Test and Ground-Based Simulation. AIAA-99-4004, Air Force Research Laboratory, Wright-Patterson AFB OH, 1999.

Shafer, M., R. Smith, and J. Stewart. Flight Test Experience with Pilot-Induced Oscillation Suppression Filters. NASA Ames Research Center, Dryden Flight Research Facility, Edwards CA, 1984.

## **Bibliography (cont.)**

Smith, Ralph H. A Theory for Longitudinal Short-Period Pilot Induced Oscillations.  
AFFDL-TR-77-57, Air Force Flight Dynamics Laboratory, Wright-Patterson  
AFB OH, June 1977.

## **Vita**

Captain Donald A. Johnson was born in Indianapolis, Indiana. He graduated from Center Grove High School, Greenwood, Indiana, in May of 1987. He earned a Bachelor of Science degree in Aeronautical Engineering and graduated with Academic Distinction from the United States Air Force Academy in 1992.

After graduation, he entered Euro-Nato Joint Jet Pilot Training (ENJJPT) at Sheppard AFB, Texas, where he was a distinguished graduate and received his wings in October 1993. As the top graduate of class 94-01, he received the AETC Commander's trophy, top formation flying trophy, and top academic award. Capt Johnson served as an F-16C wingman in the 36<sup>th</sup> Fighter Squadron, Osan AB, ROK, from November 1994 to February 1996. He later flew as an instructor and functional check-flight pilot in the 4<sup>th</sup> Fighter Squadron at Hill AFB, Utah, from April 1996 to September 1998. In October 1998, Capt Johnson returned to Sheppard AFB to serve as a T-37 instructor pilot.

He entered the joint Air Force Institute of Technology/USAF Test Pilot School program in August 1999. Upon graduating from the USAF Test Pilot School, a distinguished graduate and Liethen-Tittle award winner of Class 01A, Capt Johnson was assigned to return to fly the F-16 in the 40<sup>th</sup> Flight Test Squadron at Eglin AFB, FL.

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 074-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) 26-03-2002			2. REPORT TYPE Master's Thesis		3. DATES COVERED (From – To) Aug 2000 – Mar 2002	
4. TITLE AND SUBTITLE  SUPPRESSION OF PILOT-INDUCED OSCILLATION (PIO)			5a. CONTRACT NUMBER			
			5b. GRANT NUMBER			
			5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)  Johnson, Donald A., Capt, USAF			5d. PROJECT NUMBER			
			5e. TASK NUMBER			
			5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)  Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Building 640 WPAFB OH 45433-7765				8. PERFORMING ORGANIZATION REPORT NUMBER  AFIT/GAE/ENY/02-1		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  USAF Test Pilot School 220 S. Wolfe Ave Edwards AFB CA 93524-6485				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT  APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT  The purpose of this research was to develop a pilot-induced oscillation (PIO) suppression algorithm to operate in real-time. Specifically, this thesis sought to address the issue of PIO, the elements of a real-time oscillation verifier (ROVER), and the effectiveness of implementing ROVER with a notch filter on longitudinal pilot commands. Several previous projects have attempted to suppress PIO via rate limit pre-filters, continuously active notch filters, and predictions of PIO events. This project was different in that both rate limits and time delay PIO events were considered in conjunction with four different airframe configurations. After hundreds of ground simulations, the ROVER code was implemented in the variable-stability in-flight simulator test aircraft (VISTA). This highly modified NF-16D was flown on twelve evaluation sorties at Edwards AFB, CA during the period of 05-17 October 2001. The results of these flights showed that ROVER was over 72% accurate in detecting and suppressing PIOs. After the last sortie was flown, a parametric study of the four ROVER elements revealed an optimal setting could produce an 82% overall accuracy rate.						
15. SUBJECT TERMS  PIO suppression, real-time oscillation verifier (ROVER), pilot-induced oscillation (PIO), actuator rate limit, Test Pilot School (TPS), HAVE ROVER, VISTA, NF-16D						
16. SECURITY CLASSIFICATION OF:  a. REPORT <b>U</b>		17. LIMITATION OF ABSTRACT  b. ABSTRACT <b>U</b>		18. NUMBER OF PAGES  c. THIS PAGE <b>U</b>  <b>UU</b>	19a. NAME OF RESPONSIBLE PERSON  Bradley S. Liebst, Ph.D. AFIT/ENY	
					19b. TELEPHONE NUMBER (Include area code) (937)255-3636 Ext 4636 Bradley.Liebst@afit.af.mil	